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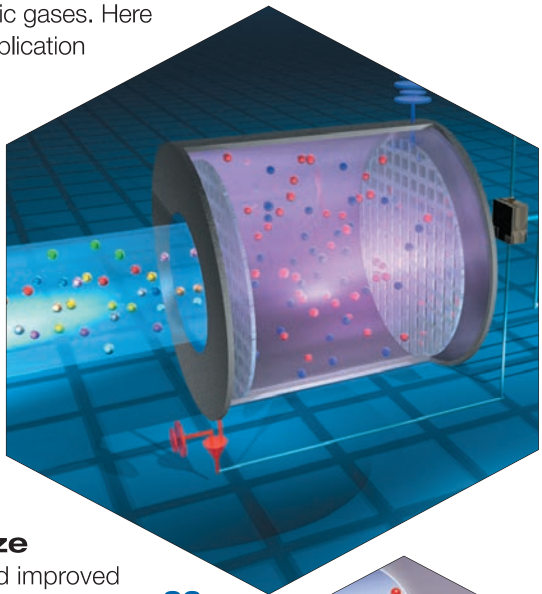
Cover Story

In the News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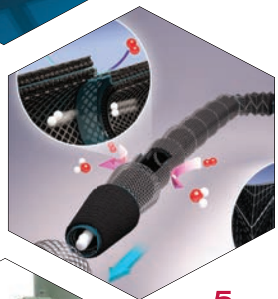
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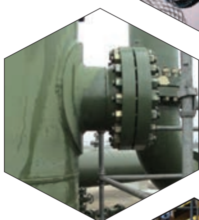
Technical and Practical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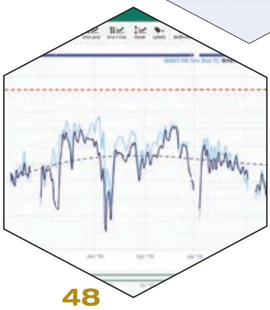

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Coming in November

Look for: **Feature Reports** on Process Control; and Construction Planning; A **Focus** on Level Measurement & Control; A **Facts at your Fingertips** on Personal Protective Equipment; a **Newsfront** on Water Treatment; a **Solids Processing** article on Particle Size Analysis; **New Products**; and much more

Cover design: Tara Bekman

Sanitize, Analyze and Optimize Bioprocessing Operations

Better designs and improved monitoring and control technologies lead to higher efficiencies

IN BRIEF

SIMPLIFYING SANITATION

MONITORING AND CONTROL

DIGITALIZATION AND MODELING

OVERCOMING FUTURE CHALLENGES

While bioprocessing can be challenging due to the sanitation requirements and exacting processes, new technologies are allowing bioprocessors to more easily sanitize, analyze and optimize their processes in order to achieve greater flexibility, tighter control, better insight and more efficiency, which leads to more predictable results and higher-quality end products.

Kevin Knopp, CEO and co-founder of 908 Devices (Boston, Mass.; www.908devices.com), says the need for optimization is increasing due to a growing biologics pipeline. "It is really an incredible time for bioprocessors as the worldwide biologics pipeline is very large right now. We estimate that there are about 4,000 assets in development today across all sorts of new modalities. About half of that pipeline is now in gene and cell therapies, and that creates a lot of complexities as they continue with development of classical monoclonal antibodies (mAbs) and add customized gene and cell therapies, which have more complex modalities.

"This creates multiple challenges," Knopp continues. "One is scaling up the process development laboratory to accommodate the rising number of assets in the pipeline, as well as handling the more complex variants and modalities in the pipeline. For this reason, bioprocessors are looking for tools and analytical gear to help them analyze and optimize the process to handle the increased workload with efficiency in order to develop a process that can accelerate a proper candidate with the necessary critical quality attributes and get it into clinical trial."

At the same time, there are additional challenges. "Hygienic design is still very demanding," adds Martin Mayer, business development of digital services with Zeta GmbH (Spatenhof, Austria; www.zeta.com). "Also, more customers are approaching us with requests for multi-purpose plants in which they want to run five or six different products. In some cases, they don't yet know what one or more of those products may be, so they need extremely high flexibility.

"Hygiene and flexibility can be obtained by combining smart design of the plant's hardware and vessels with a smart approach to how to optimize the plant," Mayer continues. "For suppliers of bioprocessing equipment, process and equipment design know-how, plant design and instrumentation and automation become the keys to delivering optimized multi-purpose plants."

Simplifying sanitation

Since bioprocesses deal with living cells, sanitation is of utmost importance. "Cross contamination can not only ruin the current batch, but processors could be subjected to losing production approval," explains Markus Kuehberger, head of business line chem/pharma at GEA Westfalia Separator (Düsseldorf, Germany; www.gea.com). "For this rea-

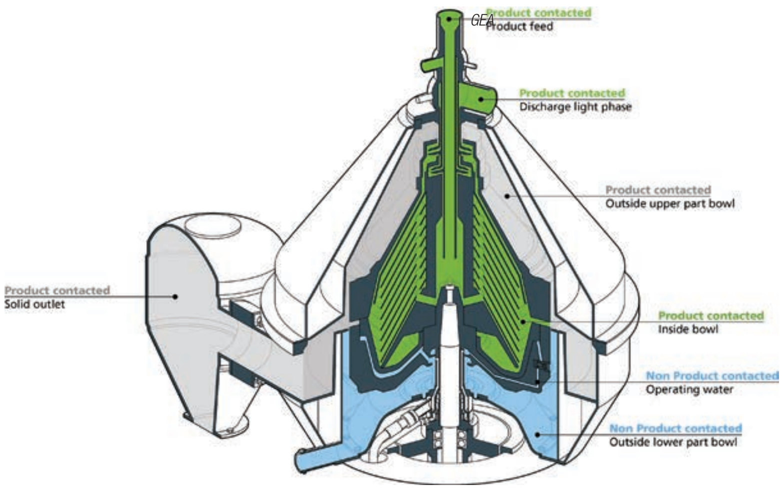


FIGURE 1. Designing an easy-to-clean centrifuge requires know-how to design the separator's geometry, as well as the piping system around it without dead spaces. It requires know-how when it comes to the treatment of stainless steel surfaces to make them as smooth as possible for better cleaning effects. Shown here are the internals of GEA's centrifugal separator

FIGURE 2. Thermo Fisher offers the Vanquish Duo UHPLC System to support two high throughput workflows (Dual LC and Tandem LC or LC-MS) by combining two flow paths in one integrated UHPLC solution

son, before beginning a batch, you must be absolutely certain that not a single cell from a former batch is still inside your system. This is highly challenging if you look at how a centrifugal separator is designed."

Inside the separator bowl is a disk-stack with inlets, outlets and many channels, which requires a lot of expertise to be sure every corner, channel and part is absolutely clean. And, of course, it helps if the separator is properly designed. "Designing an easy-to-clean centrifuge requires know-how to design the separator's geometry, as well as the piping system around it without dead spaces. It requires know-how when it comes to the treatment of stainless steel surfaces to make them as smooth as possible for better cleaning effects. Finally, it requires know-how about how to run CIP [clean in place] and SIP [steam in place] cycles in the most effective way" (Figure 1).

Kuehberger says that centrifuge design is just one side of the coin. It is the package unit that takes care of the proper CIP and SIP procedures, allowing a clean centrifuge after processing. "We bring both sides together, mount everything on a skid that is, as a unit, completely pre-tested and pre-qualified, including all necessary documentation and validation. Our customers benefit from fewer interfaces, less trouble and less time needed for validation and installation."

GEA aseptic separator skids offer efficient mAb separation that minimizes cell shearing, while the mechanical concepts and precisely adjustable ejection system ensure optimal product purity and high yield for mAb producers. The combination of the hydrohermetic inlet and bowl overflow has also been designed to achieve better CIP results. To avoid product contamination from seal abrasion, only one double mechanical seal is used. It is made of high-quality silicon carbide and is not in contact with the product.

Monitoring and control

Bioprocessing also requires a lot of control over many variables, which in turn necessitates top-notch analytical instruments. "The minute you put everything together, you have to control fermentation times and feedstock distribution and many other variables that, if not exact, can create low-quality product with changes in efficacy or immune response, so it's important to do analysis so you know what is happening with the process and to make sure the product you produce is the same every time you produce it," explains Ken Cook, EU pharma/biopharma expert support group team leader, with Thermo Fisher Scientific (Waltham, Mass.; www.thermofisher.com).

In addition to the general need for analysis, lately processors want to analyze more than one fermentation at the same time, using the same equipment, so the faster an analysis can be done, the more fermentations that can be monitored at the same time. "Speed of analysis is always a good thing and the more you can monitor, the better off you are," says Cook. Thermo Fisher offers the Thermo Scientific Vanquish Duo UHPLC System to support two high-throughput workflows (Dual LC and Tandem LC or LC-MS) by combining two flow paths in one integrated UHPLC solution (Figure 2). These workflows improve productivity by saving time, reducing cost per sample, increasing capacity without added bench space and using resources more efficiently. The company's Orbitrap Exploris 240 mass spectrometer can be coupled with the Vanquish Duo UHPLC system to further increase sample throughput and give additional information provided by high-resolution mass spectrometry analysis (HRMS). Accurate intact mass, glycan profile and additional information on spe-

cific post-translational modifications can be obtained in one analytical run through the use of HRMS as an additional detector.

However, once the sterile sampling and analysis are in place, data handling is needed to provide feedback in order to properly control the fermenter, which means there's a lot of software involved and it all has to act together, notes Cook. Thermo Scientific's Chromeleon Chromatography Data System (CDS) software can help streamline these laboratory workflows. It delivers compliance tools, networking capabilities, instrument control, automation, data processing and more. The enterprise solution is designed for tracking, accountability and quality assurance (QA) and quality control (QC).

908 Devices' Knopp agrees that analysis is a critical part of the bioprocess. "In addition to the growing biologics pipeline, there are initiatives from the FDA [U.S. Food and Drug Admin.] regarding quality by design where they want you to understand the importance of monitoring and controlling each and every process parameter and the critical quality attributes of each biologic," he says. "This puts a lot of pressure on the processor and analytical technologies and creates a major drive toward process integration, automation, control and the ability to use these analytical technologies inline."

"Historically, there has been a hinderance in taking these instruments out to the process due to the large size, complexity and expertise required to run mass spectrometers and interpret the data," says Knopp. "However, we are taking an approach that is more analogous to the computer industry in order to bring it down from centralized mainframes to desktops, laptops and mobile devices by making simple and easy-to-use desktop and hand-held mass spectrometer-based devices that are more accessible."

The company's REBEL desktop device sits beside the bioreactor and is capable of providing a quantitative list of amino acids, dipeptides, water-soluble vitamins and amines within seven minutes (Figure 3). This allows users to combine that information with other standard biochemical markers and make decisions much faster, shaving weeks off process development cycles.

Knopp says bioprocessors are showing enthusiasm at the prospect of taking a laboratory-grade answer from a mass spectrometer, moving it out to their workplace and receiving a comprehensive panel of analyses that they would historically have to send to a third-party laboratory and suffer a long turnaround for results. "They can analyze the information by looking at the output on the screen and we've made some recent integrations that allow them to take that data into other software programs they are using to perform data analysis, enabling them to look at trends and correlations within their process," he says. That information can then be used to provide insight into the process that helps improve the efficiency and quality of the process and end product, and allows them to adjust their process as needed in near real time.

Digitalization and modeling

As bioprocesses become more automated and integrated with various instruments and software programs, they are accumulating more data that should be used to further drive optimization of the process, says Zeta's Mayer. "Bioprocessing is no different from other chemical processes in that processors need to support all the data in the automation system, get it into a historian and turn the data into actionable information," he says. "This is where digitalization and modeling will begin to play a very important role and why demand for this is growing."

Zeta is currently working on a project that uses digitalization and modeling for predictive control of bioreactors, says Mayer. "In theory, this is simple: You mimic the process by applying a mathematical model that traces the entire process from the early stages to the quality at the end. If you have this model, you can use it for optimizing the process and exploring different ideas you'd like to try to improve efficiency or quality. Simply put, you get a map of the process and exploit it for some optimum you'd like to achieve," he explains.

"We wanted to have the ability

FIGURE 3. 908 Devices' REBEL desktop device sits beside the bioreactor and is capable of providing a quantitative list of amino acids, dipeptides, water soluble vitamins and amines within seven minutes. This allows users to combine that information with other standard biochemical markers and make decisions much faster, shaving weeks off process development cycles

to control bioreactors based on a model," he says. The company recently began a project with two large pharmaceutical companies in order to explore the potential business and commercial benefits behind the bioreactor-modeling concept. By the end of 2021, Zeta expects to have a working prototype that would allow the pharmaceutical companies to experiment with options, such as: "I want to reduce my fermentation time by 8%. What parameters can be changed to meet that goal without sacrificing quality?" or "How can I combine unit operations and optimize operations such as fermentation, screening and downstream processes to run one after the other to get an overall optimum instead of a local optimum?"

There are many different ideas on how this technology may be applied to improve operations and optimize the process, but processors have to know early enough in the process development phase to create an accurate model in order to take the model through all the validation steps, says Mayer. "This is one of the reasons this technology has not yet been applied in the bioprocessing industry, so we are working on this project as a proof of concept to show end users that modeling control does provide value."

Overcoming future challenges

As the upstream part of the process continues to evolve, the downstream side faces its own set of challenges, says Patrick Farquet, head renewables and bio-based applications with Sulzer Chemtech (Winterthur,

FIGURE 4. Often, technology providers rely on extractions using solvents to extract ingredients or biochemicals from highly diluted feeds and proven crystallization techniques to reach the desired purity. Shown here is a large liquid-liquid extraction column

Switzerland; www.sulzer.com). "The challenges on the downstream side are coming from the upstream part of the process," he says. "They create dilute streams that contain a lot of water and a mix of different products. This mix of smaller impurities makes it difficult to concentrate and purify the one product they want to have. Furthering the challenge is the range of natural feedstocks that often have some seasonality or process differences that generate varying impurities with time. Often, in the lab, biotech companies will use one set of techniques to purify, but, from a cost perspective, are nearly impossible to replicate on an industrial scale. While it seems feasible to make 100 grams, making 10 tons continuously is often a challenge."

While the laboratory may use liquid chromatography or difficult solvent-crystallization methods to achieve their results, they often prove to be impossible to scale up, so providers such as Sulzer must find ways to use standard techniques, such as extraction, to make the downstream process profitable and scalable. Finding the technique that provides the desired outcome in a way that is profitable requires pilot testing and tweaking of existing technologies. "If you look at the chemical industry, the most widely used separation technology is distillation," Farquet says. "We still use it, but in most bioprocessing applications, it works for concentration stages, but it is unlikely you will get to the necessary final purity levels just by using distillation techniques." Often technology providers rely on extractions using solvents to extract ingredients (Figure 4) or biochemicals from highly diluted feeds and proven crystallization techniques to reach the desired purity. In other cases, they may employ techniques like adsorptions to adsorb organic impurities that can't be removed via traditional technologies. "All sorts of techniques have to be examined, tested and possibly combined in order to find the method that works best to get the product that is needed with a reasonable cost," he says.

Pramod Kumbhar, CTO with Praj Industries (Pune, India; www.praj.net) agrees that scaling up can be difficult, especially as processors are moving toward continuous processing versus batch. "With a mindshare towards continuous manufacturing in the biotech space, high-capacity plants that are planned to provide economies of scale create two challenges: handling large volumes calls for very high capital expenses and increases the risk involved. Gradual scale up of output without very high capital expenses and fewer risks or problems due to lower volume handling call for deeper engagement at the process development stage," says Kumbhar. "This also means we need to focus on all the disciplines of the plant, including process, infrastructure and automation. And for the connected world, there is a growing need to make the system future-ready. This calls for a different thought process going forward that involves plant automation, integration, data management and predictability," he says.

"Centralized process-automation solutions will have to be integrated with enterprise software to manage inventory, process data, proactive maintenance and real time records. This will form the foundation for artificial intelligence in process plants and will be the eventual future of bioprocessing," says Kumbhar. ■

Joy LePree

Laboratory Equipment

GEA Group

Entex Rust & Mitschke

Hauschild SpeedMixer

IKA-Werke

Laboratory homogenizer for challenging products

The TriplexPanda Lab Homogenizer (photo) is a three-piston tabletop unit for the treatment of emulsions, dispersions and nanoparticles. Thanks to high-grade, high-performance super duplex stainless steel, plus special, highly wear-resistant materials, the machine can operate with a very wide range of products. As an appropriate choice for product development and small production batches between 1 and 100 L/h, this special design also enables the TriplexPanda to process challenging products, such as sticky or highly viscous emulsions, preparations with micro and nanofibers, as well as products containing pieces or crystals. The homogenizer is available in two versions for continuous operation up to 400 bars with a maximum flowrate of 100 L/h or 600 bars for up to 60 L/h. — *GEA Group AG, Düsseldorf, Germany*
www.gea.com

A new generation of laboratory roller extruder

The L-WE 30 laboratory roller extruder (photo) is a multifunctional, compact compounding system. The modular process section can be extended to up to six roller cylinders. This allows the creation of specifically adapted process zones, which can be configured in a targeted manner with regard to tempering and mechanical influencing variables. The L-WE 30 is suitable for the development of new products and manufacturing processes or the production of very small quantities. A wide range of process applications are possible, including compounding, chemical reactions, recycling, food processing, mixing and dispersing, degassing, drying and cooling. The unit has a throughput capacity of 0.5–10 kg/h, a drive power of 10 kW and an extruder speed of up to 1,000 rpm. The system operates over the temperature range of –20 to 330°C. — *Entex Rust & Mitschke GmbH, Bochum, Germany*
www.entex.de

A new era of laboratory mixing with this smart machine

The recently introduced new series of intelligent DAC (dual asymmetric centrifugal) mixers, the SpeedMixer Smart DAC Series (photo), features real-time temperature control; vacuum-robotic; sensor integration; variable counter rotation; Internet-of-things compliance; QR-code reader; remote control; and automatic pot cooling system. Furthermore, the company has increased the capacity of its SpeedMixer, offering more choices for specific applications. The Smart DAC series allows mixing from 250 g up to 1.5 kg and 2 kg. All Smart DAC models will be available with mixing volume from 310 mL up to 2.8 L. Up to 20% more powerful than the standard LR version, the Smart DAC features variable counter rotation, increased mixing weight and volume and allows up to 30 min. of mixing time. — *Hauschild SpeedMixer Inc., Farmington Hills, Mich.*
www.hauschild-speedmixer.com

A new, compact recirculating chiller

The RC 2 lite recirculation chiller (photo) has a 400-W cooling capacity and a pump pressure of 0.35 bars. The new recirculating chiller is said to be space-saving, powerful and extremely economical. It is ideal for simple cooling tasks down to –10°C and as a supplementary device to rotary evaporators, reflux coolers and cold traps. Thanks to the minimum filling volume of just 1 L, the RC 2 lite is able to carry out temperature changes very quickly if necessary. Its working volume of 2.5 L, which is quite large considering its compact size, enables a large number of external applications without the need for refilling. — *IKA-Werke GmbH & Co. KG, Staufen, Germany*
www.ika.com

Efficient solvent recovery for fast evaporation tasks

The Huber CT50 cold trap (photo, p. 20) offers direct, rapid cooling to temperatures as low as –50°C, as

Huber Kältemaschinenbau

Hemco

Fritsch

Avantor

Anton Paar

well as low operating costs. Its compact design takes up minimal space on the laboratory bench. It is also robust and durable due to the high-quality materials used in its manufacture. The evaporator is made of stainless steel, and on request, can be coated with resistant polytetrafluoroethylene, ceramic polymers and more. The cold trap comes with a drip tray, and a glass accessory set is also available to order. The cold trap has been developed to offer highly efficient solvent recovery in laboratory conditions. It can be connected to rotary evaporators or any other application requiring low temperatures for solvent recovery. — *Huber Kältemaschinenbau AG, Offenburg, Germany*
www.huber-online.com

A fume-hood scrubber for corrosive fumes

The Inline Fume Scrubber (photo) removes highly corrosive and acid fumes from individual laboratory fume hoods. The scrubber is constructed of chemical-resistant materials, is compact and features a vertical venture design. The scrubber has a low operating cost and requires a low flowrate (8 gal/h) of water for operation. There are no moving parts and a complete recirculation system option is available, including recirculation tank and pump, pH controls, feed tubing, and chemical-feed tank and pump. — *Hemco Corp., Independence, Mo.*
www.hemcocorp.com

Planetary mills for laboratory applications

The planetary mills premium line (photo) are extremely strong, all-purpose mills that are said to offer premium performance, usability and safety. Due to rotational speeds of up to 1,100 rpm, ultra-fine milling results are achieved by powerful wet and dry comminution of hard, medium-hard, soft, brittle and moist samples by the high-energy impact of grinding balls in rotating grinding bowls. The advantages include extremely short grinding times and reliably reproducible results down into the nanometer range. These mills are also suitable for highly efficient mixing and homogenizing, or for mechanical activation and alloying in materials research. — *Fritsch GmbH, Idar-Oberstein, Germany*
www.fritsch.de

Robotic tips for liquid-handling systems

This company recently introduced J.T.Baker premium robotic tips (photo) for use with leading robotic liquid-handling and research workstations. Engineered to help scientists and researchers move from discovery to delivery faster, the tips are ideal for a range of applications, from genomics and cell biology to proteomic workflows. The tips are offered in two formats: conductive and clear. J.T.Baker conductive robotic tips are engineered to minimize downtime and keep operations running smoothly. Their proven design enables even small liquid volumes to be sampled with high precision and without contamination. J.T.Baker clear robotic tips are for both sample preparation and drug discovery applications. The transparent tips enable visual recognition of foam to help ensure proper sampling. — *Avantor, Inc., Radnor, Pa.*
www.avantorsciences.com

These density meters are very accurate

This company recently introduced the new Next-Level Density Meter (photo). Driven by the unique pulsed excitation method (PEM), the instrument guarantees an accuracy of 0.000005 g/cm^3, making it the most accurate density meter in the world, the company says. The new series has also fulfilled the demands of a modern, digital measuring system: high-speed operating system, increased memory with fast data export, high-resolution zoom camera and high-end touchscreen performance are now standard. The new instruments connect to a wide range of data interfaces, including the company's new AP-Connect data-management platform. There are three models in the new series: DMA 4101, the fastest and most efficient measurement for quality control; DMA 4501, an all-purpose device for all industries; DMA 5001, the highest precision for demanding samples and best performance in demanding, high-end applications. — *Anton Paar GmbH, Graz, Austria*
www.anton-paar.com

Improve accuracy and safety with this automatic balance

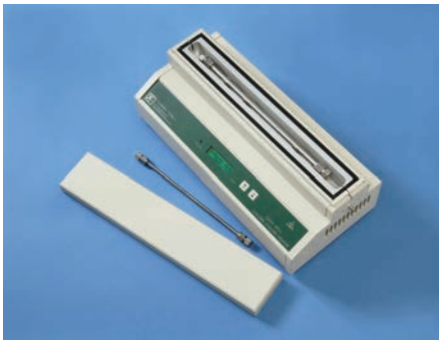
The new XPR Automatic Balance (photo, p. 21) incorporates state-of-the-art active machine learning to

deliver accurate powder weighing. Safety when weighing potentially toxic or active substances is of paramount importance in industries such as chemical, pharmaceutical and biotechnology. The XPR Automatic supports accuracy, repeatability and safety by dosing from an enclosed head into target vials or capsules with openings as small as 6 mm in diameter. It then uses live feedback to learn a substance's flow characteristics and improve dispensing efficiency in real time. This can be particularly effective when combined with a sample changer that can process as many as 30 samples in one automated run. Direct dosing reduces the kind of airborne exposure risk to lungs and eyes that spatula use represents. Spill risk is also eliminated, as is the need to repeatedly open the balance door and transfer compounds from the main container into a secondary container. The balance can be operated inside a glove box or safety enclosure. — *Mettler Toledo, Columbus, Ohio*
www.mt.com/lab

Mettler Toledo

Heat or chill HPLC columns with this unit

The EchoTherm Model CO50 (photo) is a programmable chiller/heater for high-performance liquid chromatography (HPLC) columns. The unit has a temperature range from 4.0 to 100.0°C (readable and settable to 0.1°C). The PID control software regulates temperatures to ±0.2°C, even at ambient conditions. The CO50 has an LED indicator that illuminates when the target temperature is stable to within ±0.2°C. The Peltier-based CO50 has five-program memory of 10 steps per program and the ability to repeat any program from 1 to 99 times automatically. It is suitable for chiral and biomedical chromatography where below ambient temperatures help preserve bioactivity. It can be used for stabilizing column temperatures from day to day at or near room temperatures for repeatable results. The CO50 holds columns up to 30-cm long with 1/4- or 3/8-in. diameter mounting clips provided. Larger-diameter columns can be used by



Torrey Pines Scientific

removing the column clips. — *Torrey Pines Scientific, Inc., Carlsbad, Calif.*
www.torreypinesscientific.com

Crimping machines for the laboratory and production

This company recently introduced a lineup of semi- and fully automatic vial-crimping machines. Offering a clean, consistent crimp for the full range of manufacturing applications — from R&D through scaleup and large-batch production — the CrimpTech series utilizes a four-jaw collet approach to ensure safe, dependable sealing. The crimpers can handle vials in a wide variety of shapes and sizes, and feature easy, toolless changeover for simplified operation and minimized downtime. The fully automatic version can process up to 50 containers per minute, with caps fed via a stainless-steel vibratory feeder. The unit's novel approach to cap placement and crimping ensures each item is stopper-tamped prior to crimping for a reliably level seal. The CrimpTech Benchtop (photo) is a semi-automatic unit whose ability to be placed under laminar flow hoods makes it suitable for aseptic and cleanroom applications. The portable unit is suitable for R&D and pre-production efforts. It is simple to maintain and exceedingly cost-effective, the company says. The CrimpTech Standalone is an automatic tabletop module where pre-stoppered vials enter and exit via tray. The reliable unit offers fast, simple collet changeover for different cap styles or, for vials of various diameters, fast star wheel replacement.— *TurboFil Packaging Machines LLC, Mount Vernon, N.Y.*
www.turbofil.com

Glassware washers earn ACT Label certification

The Miele PG 8583 and PG 8593 glassware washers have both earned the ACT Label from My Green Labs, a non-profit organization dedicated to creating a culture of sustainability in science. The ACT acronym (accountability, consistency and transparency) shows how products "rate" in sustainability-related categories. The PG 8583 glassware washer received Environmental Impact Factor — a sum of verified information on a product's energy consumption, water use, and end-of-life considerations — of 72.5; the PG 8593 glassware washer scored 76.6. The company's full portfolio of laboratory glassware washers are ideally suited for service in laboratories dedicated to clinical diagnostics, pharmaceutical, biotech, food and beverage, specialty and petrochemicals, water and wastewater treatment, environmental testing, general industrial, education and medical research. — *Miele Professional, Princeton, N.J.*
www.mieleusa.com ■

Gerald Ondrey

Pneumatic Conveying: Pipeline Design Considerations

Department Editor: Scott Jenkins

Attention to the design of bulk-solids pneumatic-conveying pipelines can help avoid conveying-system problems, such as low conveying rates, plugging, excessive wear-and-tear in the conveying line, high conveying-system pressure drop, product breakage, fines generation and product cross-contamination. This one-page reference provides general guidelines to help mitigate or avoid such problems in pneumatic conveying operations.

Materials of construction. Pipes should be made from carbon steel if contamination is not an issue. Use stainless steel for food and pharmaceutical applications. For special applications with abrasive solids, high temperatures, and so on, it is necessary to find a suitable material for the conveying line and its components.

Pressure rating. The pressure rating of the conveying pipeline should be suitable for the maximum conveying pressure of the conveying system. For most applications that have a Roots-type blower, a pressure rating of 30 psig is satisfactory. This rating corresponds to the rating of a Schedule 10 pipe. Use thicker pipes for higher-pressure applications.

Temperature rating. The temperature rating of the conveying pipeline should be suitable for the minimum and maximum temperatures experienced by the conveying line. These temperatures depend upon the ambient temperature, conveying air temperature and solids temperature.

Pipeline joints. Pipeline segments should not be welded to each other because the pipeline may need to be dismantled. Flanges can be used, but they are expensive and not easy to unbolt. So flanges should be used where the joint must be 100% leak-proof. Otherwise, use easy-to-open pipeline couplings. Locate the joints for easy access. The inside diameter of the couplings or the flanges must be equal to the inside diameter of the pipe. Ends of adjacent pipe segments must be truly aligned so there is no internal protrusion and no gap between the two ends.

Pipeline internal surface. The inside surface should be clean and free of oil and rust. A smooth interior can be used, except when handling plastics that can generate so-called streamers, which are formed when a plastic particle at a high conveying velocity strikes the smooth pipe wall at a low angle of incidence. The energy of impact is enough to melt the particle surface at the point of contact and leave a thin crayon-like film mark on the pipe wall. This thin film continues to grow due to subsequent impacts, cools quickly, and peels off from the pipe wall in the shape of a streamer. The net result of streamers is plugged slide gates, feeders, screeners, mechanical conveyers and hoppers. To avoid making streamers, the inside surface of the pipeline is roughened. Although scoring is recommended for conveying systems that handle soft plastics, it has two distinct disadvantages. Pressure drop through the conveying system is higher than that in smooth pipes, and some particle attrition results because of the roughened surface.

Static charges. When handling solids that generate static charge, pipelines must be built to conduct this charge to the ground. Pipeline joints must allow this charge to flow to the ground by using static conducting jumpers across each joint. After assembly of the pipeline, check its resistance to ground, from the beginning to the end. It should not exceed 1 Ohm.

Pipeline supports. Pipes come in standard 20-ft lengths. Therefore, provide supports for the pipeline at least every 20 feet. Locate these supports to prevent any sags in the pipeline due to its weight. After installation, make sure that the pipeline is straight and not sagging. If the pipeline can expand due to high temperatures, design the supports to allow for this expansion. Locate the pipeline so that it has easy access for dismantling.

Bends. Material of construction, pressure rating and temperature rating of the bends should be the same as that of the pipe. Standard short-radius bends are not used in conveying lines because of pressure drop considerations. Studies show that long-radius bends have a lower pressure drop. Long-radius bends with a bend-radius-to-pipe-diameter ratio between 8 and 10 have a lower pressure drop (Figure 1). Some vendors have developed special bends to reduce product degradation and bend erosion.

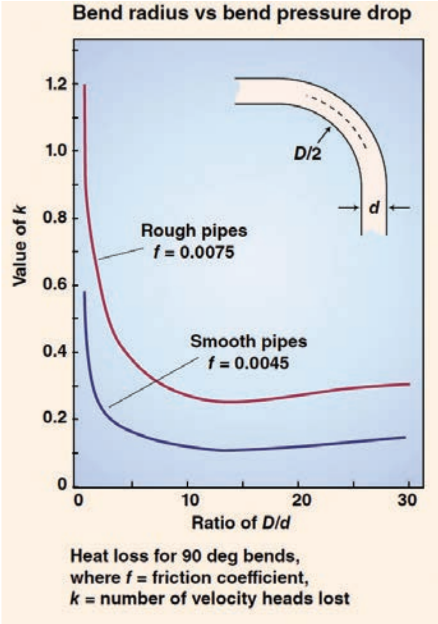


FIGURE 1. Long-radius bends in pneumatic conveying systems give rise to lower pressure drop than short-radius bends, which are generally not used in conveying lines

Air or gas supply line. Keep the length of the air or gas supply line as short as possible by locating the blower close to the solids inlet or outlet point. Minimize the pressure drop in this line by using a large-diameter line if needed. Carbon-steel construction can be used, except for in food and pharmaceutical applications. Pressure and temperature rating can be the same as that of the conveying pipe. Provide a check valve in this line upstream of the solids inlet (for pressure-type systems), or downstream of the outlet point (for vacuum-type systems) to prevent solids from backing-up into the conveying blower. ■

Editor's note: The material in this column was adapted from the following article: Agarwal, A., Rules of Thumb for Pneumatic Conveying Pipelines, *Chem. Eng.*, May 2012, pp. 51–55.

Monitoring Ammonia and Other Toxic Gas Hazards

There are many technologies used in industry to protect workers from toxic gases. Here are some guidelines for selecting one that will match your application

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The dual threat of toxicity and combustibility applies to a number of industrial gas hazards. When such gases go undetected, they can lead to catastrophic accidents with the potential to injure or kill employees and damage or destroy plant equipment. Ammonia is one of those potentially double-trouble hazards, especially in its most common usages as a refrigerant or fertilizer product. It can be found as a chiller or refrigerant in the food and beverage industry, pharmaceutical production, in air-conditioning equipment, in electric power generation plants and, of course, fertilizer production. Understanding the proper precautions to take with ammonia provides a highly useful model or example of what is required when protecting people, equipment and plants against the threats of many other toxic and combustible gases. In general, those responsible for plant processes and safety need to understand the health threat and symptoms of exposure to any toxic gas, the nature of any toxic or combustible gas (how it behaves in a plant setting) and the gas detection sensing technologies available. The article explains the advantages and limitations of gas detection technologies, as well as their maintenance requirements.

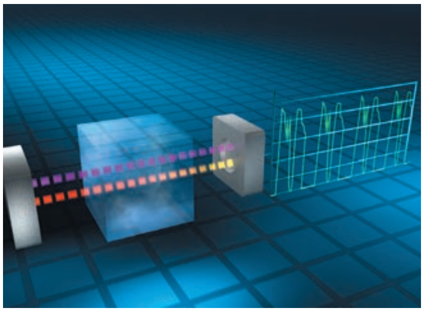

FIGURE 1. Optical infrared sensors offer a high specificity for ammonia without degradation when exposed to high concentrations

Understanding the gas

According to the U.S. Occupational Safety & Health Administration (OSHA; Washington, D.C.; www.osha.gov): "Ammonia is considered a high health hazard because it is corrosive to the skin, eyes and lungs. Exposure to 300 parts per million (ppm) is immediately dangerous to life and health. Ammonia is also flammable at concentrations of approximately 15 to 28% by volume in air."

OSHA also correctly points out that when ammonia is mixed with lubricating oils, its flammable concentration range increases. It can explode if released in an enclosed space with a source of ignition present, or if a vessel containing anhydrous ammonia is exposed to fire. Fortunately, ammonia has a low odor threshold of 5 ppm, so most people will seek relief at much lower concentrations.

How gas behaves in the plant

Toxic gases, including ammonia, can be difficult to detect, depending on the specific gas and the plant layout. For example, fertilizer plants are typically crowded with equipment where ammonia can be present. The same can be said for many other materials-processing or other industrial plants where ammonia is present as a refrigerant gas for chilling or refrigeration. Layered, redundant monitoring gas-detection sensing technologies provide an added degree of safety against toxic and combustible gases, such as ammonia.

Leaking ammonia also tends to form clouds outside plant buildings that are affected by temperature and weather. These clouds also have the potential to travel beyond the plant perimeter, potentially endangering other nearby facilities or the community at large. For these reasons, plant safety teams typically rely on a mix of portable detectors worn by employees and plant fixed-gas detection systems, including perimeter monitoring.

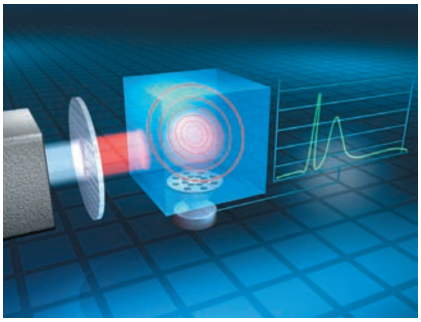

FIGURE 2. Photoacoustic infrared sensors can continuously detect ammonia at very low concentrations without the need for a reference point

Gas detection and sensing

There are several types of fixed-gas detectors that are appropriate for protecting plants from toxic gases. Point detectors relying on infrared (IR), electrochemical cell or other contact sensing technologies are typically placed throughout the plant near equipment in production areas, on pumps, valves, pipelines and tanks for loading and unloading. Along plant exterior boundary fence lines, perimeter detectors are placed. These detectors rely on open-path detection technologies.

Many types of fixed-gas sensors

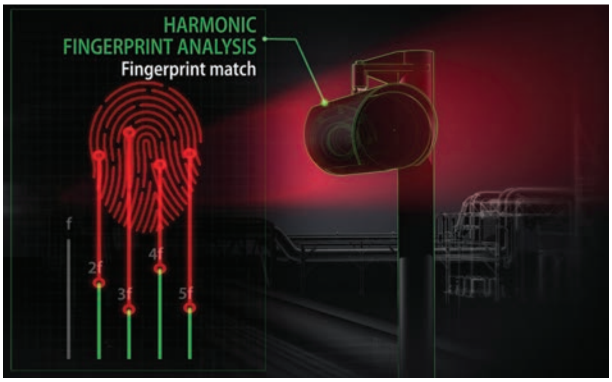

FIGURE 3. Enhanced laser diode spectroscopy can be used to detect specific gases without false alarms from interference gases or water vapor

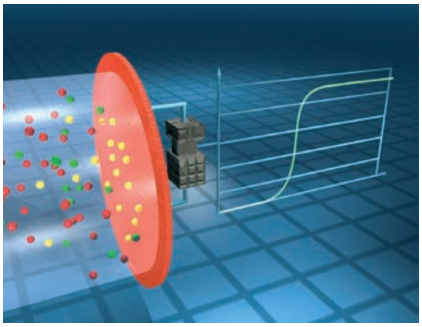

FIGURE 4. The detection mechanism of metal-oxide semiconductor sensors involves the measurement of conductivity as the target gas is oxidized on the sensing element

are available to detect ammonia vapor and other toxic or combustible gases within industrial applications. The following sections look at the operating principles behind these technologies with an eye toward understanding their strengths and potential weaknesses.

Optical infrared technologies

Optical infrared (IR) sensors have been used for decades to monitor combustible and toxic gas leaks, including ammonia (Figure 1). The key benefits of IR sensors are their high specificity to ammonia and reduced (or even eliminated) need for calibration adjustment. IR detectors have a wide dynamic range and are not degraded or consumed by exposure to high concentrations of ammonia. Their main limitations are the physical size of the detector assembly, the need to protect the detector against the potential effects of fluctuating temperature and humidity and higher cost compared to other detectors.

Differential infrared. Differential IR sensors measure gas as a function of the absorbance of infrared light. Molecules consist of atoms that are held together by chemical bonds. The bonds in a particular type of molecule (such as ammonia) absorb energy at selected wavelengths. When a chemical bond absorbs infrared light, it continues to vibrate at the same frequency, but with greater amplitude after the transfer of energy. In other words, molecules that can absorb energy at that wavelength are heated to a higher temperature than molecules that are not able to absorb light at that wavelength.

When IR radiation passes through a sensing chamber containing a specific gas, the only wavelengths that are absorbed are the wavelengths that match the chemical bonds in that gas. The rest of the light is transmitted through the chamber without hindrance. As most chemical compounds absorb at several different frequencies, IR absorbance can be used for measuring the gas concentration.

TDL absorption spectroscopy

Alternatively, for some molecules, it can be possible to find an absorbance peak at a specific wavelength that is not shared by other molecules that may be present. In this case, absorbance at a particular wavelength can be used to provide a substance-specific measurement for a specific molecule. This is possible for some molecules, including

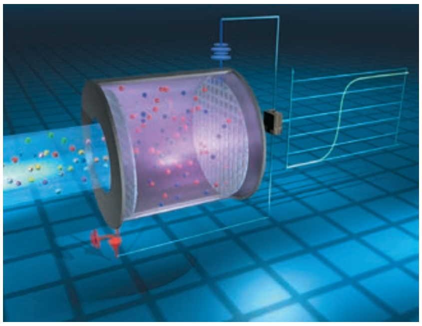

FIGURE 5. In an electrochemical sensor, the target gas contacts a catalytic electrode site and an electrolytic solution, and electrons are released. By measuring this current, the presence of the target gas can be determined by the sensor

ammonia, which has a usable absorbance peak at a wavelength of about 1,512.2 nm using laser-based IR detection technology. Absorbance at this wavelength is proportional to the concentration of ammonia.

Tunable diode laser (TDL) absorption spectroscopy technology is used by open-path gas detectors operating similarly to point IR gas detectors. The difference between the two technologies is the distance between the light source and the receiver, which for open-path gas detectors can be more than 330 ft (100 m). The system cannot determine the size of the cloud or its concentration, so it calculates the total amount of the specific wavelength being absorbed by the gas. This calculation then determines the concentration of gas between the source and the receiver and is represented in the measurement range of ppm meters.

PAIR sensing technology

Photoacoustic infrared (PAIR) analysis extends beyond simply measuring the amount of infrared light that is absorbed, which is the case for the nondispersive infrared (NDIR) monitors described earlier. This technology actually detects what occurs after the gas is absorbed. Photoacoustic sensor technology is ideal for detecting ammonia at very low concentrations (as low as 10 ppm). It offers zero stability, eliminating the need for zero drift adjustment. A direct gas reading is obtained because there is no need for a reference point, ensuring continuous monitoring. No zero point is involved, providing the most accurate and reliable readings.

When using a PAIR instrument (Figure 2), a gas sample is introduced into the monitor's measurement chamber and the sample is exposed to a specific wavelength of infrared light. If the sample contains the gas of interest, that sample will absorb an amount of infrared light proportional to the gas concentration that is present in the sample. Gas molecules are always in motion and move around the inside of the measurement chamber, generating pressure. When gases absorb infrared light, the temperature of the molecules rises, and they begin to move more rapidly. As a result, the measurement chamber pressure increases, creating an audible pulse that can be detected.

A highly sensitive microphone is located inside the photoacoustic infrared monitor to detect even the smallest of pressure pulses, enabling detection of very low levels of gas. As the optical filter will only pass the particular wavelength of light for the gas in question, a pressure pulse indicates that the gas is present. The premise is simple; if no pressure pulse occurs, then no gas is present. The magnitude of the pressure pulse indicates the gas concentration present. The stronger the pressure pulse, the more gas that exists.

ELDS technology

Another technology using the effect of absorption of specific optical light by ammonia is laser-based open-path gas detectors. This sensor technology utilizes enhanced laser diode spectroscopy (ELDS). Unlike point NDIR or other point gas detectors that simply measure the gas concentration at a particular (fixed) location, ELDS gas detectors measure the concentration (in ppm per m or ppm-m) over the full distance between the transmitter unit and receiver unit.

ELDS open-path detectors analyze the signal using a technique called Fourier transform, which breaks the signal into several component parts that can be analyzed against a predetermined pattern that is similar to a harmonic fingerprint (Figure 3). This means there are no false alarms from interference gases, the detectors are less prone to water-vapor interference, and they provide greater reliability and performance in rain or fog.

The ELDS transmitter/receiver configuration is failsafe, which improves the level of safety. It also does not require calibration or any other routine maintenance and has no consumable parts, resulting in a low cost of ownership. With a built-in automatic self-testing function, an ELDS sensor offers end users a solution to the problem of costly and time-consuming testing of gas detectors.

MOS sensors

Metal-oxide semiconductor (MOS) sensors, also known as chemisorption sensors, consist of a metal-oxide semiconductor, such as tin dioxide (SnO_2) on a sintered alumina ceramic bead contained within a flame arrestor (Figure 4). In clean air, the electrical conductivity is low. Oxidation of the measured gas on the sensing element increases conductivity. An electrical circuit is used to convert the change in conductivity to an output signal which corresponds to the gas concentration. Sensitivity to a particular gas is measured by changing the temperature of the

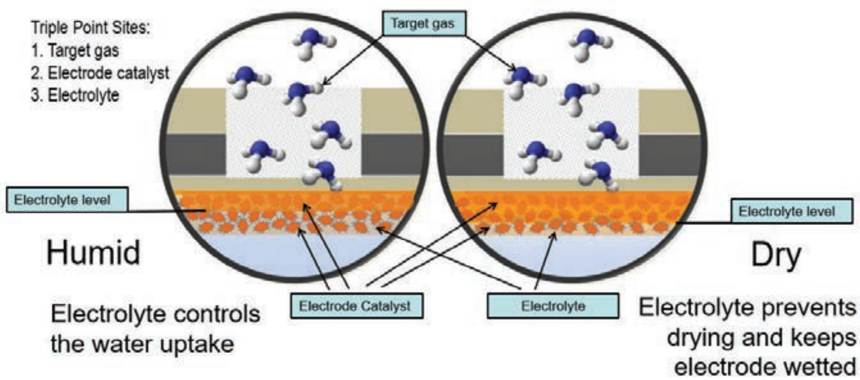

FIGURE 6. The electrolytic solution in an electrochemical sensor is consumed as the sensor is exposed to the target gas

sensing element.

MOS sensors are designed to respond to the widest possible range of toxic and flammable gases and vapors. The idea is to provide a "broad range" response to the presence of contaminants. MOS sensors can detect chlorofluorocarbon refrigerants, as well as other gases that are difficult to detect by other means, as well as ammonia, carbon monoxide, hydrogen, alcohols and many other gases and vapors.

Their non-specificity is advantageous where unknown toxic gases are present, and a simple go/no-go determination is sufficient. As the sensors are not specific to ammonia, however, this can lead to false alarms if the sensors are installed where interfering contaminants are present. The benefits of MOS sensors are their long operational life and low cost. MOS sensors can be used to detect ammonia concentrations as low as 30 ppm, up to concentrations in the flammable range.

Electrochemical sensors

Target-gas-specific electrochemical (EC) sensors are available for many of the most common toxic gases. Electrochemical sensors are compact, require very little power, exhibit excellent linearity and repeatability, and are comparatively inexpensive. The detection technique is very straightforward in concept.

Electrochemical sensors function on principles similar to those found in batteries. The target gas enters the sensor through an inlet, and then generates a chemical reaction with a catalyst that is in contact with an electrode. When the target gas encounters an electrolyte solution on the working electrode, a reaction occurs (Figure 5).

This reaction causes a release of electrons, whereby the flow of the electrons is measured as current within the sensor. Consequently, the current is proportional to the gas concentration and the reaction is measured in ppm of the gas. In the case of ammonia sensors, the electrolyte includes an active ingredient that is consumed in the electrochemical reaction used to detect the ammonia. Thus, the lifespan of the sensor is directly related to its amount of exposure to ammonia.

The sensor is filled with an organic gel electrolyte mixture in which the reaction occurs (Figure 6). Active ingredients in the electrolyte are incrementally consumed as the sensor is exposed to ammonia. Once the exposure life of the sensor is exceeded, it is no longer capable of detecting gas, and will need to be replaced. Next-generation technology utilizing ionic-liquid electrolytes have an extremely low vapor pressure, and they do not evaporate in extreme environments, even with long periods of low humidity. The positive benefits for this type of sensor include good resolution in the low-ppm range and acceptable cold-temperature performance.

Catalytic bead sensors

These sensors use a catalytic bead to oxidize mainly combustible gases, but also higher-volume-percentage concentrations of ammonia (Figure 7). A bead is represented by wire coil coated with a catalyst-coated glass or ceramic material and is electrically heated to a temperature that allows it to burn the gas being monitored, releasing heat

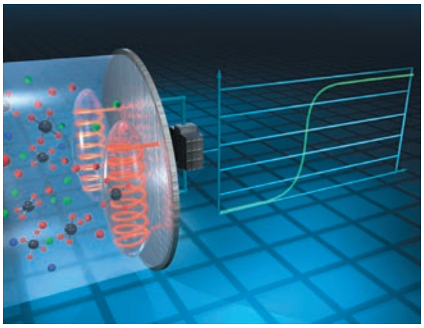

FIGURE 7. Catalytic bead sensors are mainly used to oxidize combustible gases, but they can also be used in high-volume ammonia applications

and increasing the temperature of the wire. As the temperature of the wire increases, so does its electrical resistance. This resistance is measured by a Wheatstone bridge circuit, and the resulting measurement is converted to an electrical signal used by gas detectors. Usually a second sensor, the reference bead, is used to compensate for temperature, pressure and humidity. These sensors have a long life and are less sensitive to temperature, humidity, condensation and pressure changes. However, they are also subject to sensor poisoning and shortened life with frequent or continuous exposure to high measured-gas concentrations. Another limitation is that they monitor a wide range of combustible gases and vapors in air, and therefore are not specific to ammonia gas.

Keys to success

It is important to understand that no single type of toxic or combustible gas sensor is perfect or foolproof in all industries and applications. The keys to gas monitoring that drive success are understanding the following:

- The human gas exposure symptoms and health issues
- The physical properties of the gas hazard
- The plant's geographic location and the plant physical site environment
- The potential gas leak sources and location where detectors must be placed
- The applicable choices of sensor technologies and their advantages and limitations
- The chosen detector's calibration and installation requirements
- The detector's maintenance requirements and its lifecycle

Many of the mature and the newer sensing technologies have improved through evolving designs, materials advances and better construction technologies. In addition, sensors are now highly intelligent compared to 20 to 30 years ago with benefits that include diagnostics, self-regulation and network communication with other process safety systems in the cloud for remote monitoring. ■

Edited by Mary Page Bailey

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Bolt-Load Considerations Associated with 'Hot Bolting'

In some situations, it might be necessary to remove or replace a bolt during operation. This article shows how to determine the proper bolt load to prevent leaks

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IN BRIEF

Bolted flange joints (Figure 1) are part of pressure vessel and piping components and are extensively used in the chemical, petrochemical, fertilizer and the oil-and-gas industries. They are simple structures and offer the possibility of disassembly, which makes them attractive to connect pressurized equipment and piping. In addition to being prone to leakage, they often require maintenance while in operation, in which case, the bolts are either re-tightened as in hot torquing or un-tightened to be replaced. Although costly shutdowns are avoided, such maintenance work exposes the operator to a potential risk because bolt load alteration can produce a gasket load unbalance, which results in the local gasket contact stress to drop below some critical value, causing a major leak and hence jeopardizing the life of the worker. The distribution of contact stress has a dominant effect on sealing performance, while the sealing capability of joints is related to the contact pressure (gasket stress) during operating conditions, providing possible leakage and ultimately joint failure. This article addresses the bolt load required in the remaining bolts to prevent leakage.

FIGURE 1. Bolted flange joints, such as those shown here, are a common sight at production sites

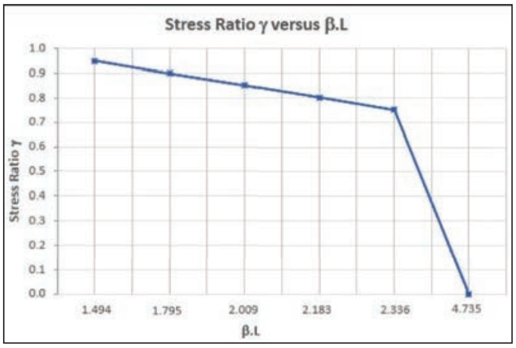

FIGURE 2. This graph shows a plot of the stress ratio γ versus $\beta \times L$

Introduction

Hot bolting is the procedure or practice of replacing bolts in a flange connection while the pipeline or equipment is still in service. This article focuses in particular on the required bolt force to be achieved during the re-tightening process. The criterion for the analysis is to ensure gasket pressure is maintained to a sufficient level during hot bolting to prevent leakage when the bolt load is reduced. The solution must account for the flexibility of the flange because the absence of a bolt increases the distance between applied bolts. The reduction in gasket stress will be largest at the point halfway between the bolts adjacent to the location of the removed bolt. The solution is based upon finding the bolt stress that must be present in the remaining bolts to satisfy the gasket pressure criterion. Moreover the resulting solution takes into account gasket pressure criterion, flange flexibility, internal pressure and flange loads.

Approach and assumptions

The approach requires that the stress in the gasket is sufficient to maintain a seal during

TABLE 1. TARGET VALUES OF β X L FOR SPECIFIC ALLOWABLE VALUES OF γ	
Stress Ratio γ	**β x L**
0.95	1.494
0.9	1.795
0.85	2.009
0.8	2.183
0.75	2.336
0	4.735

hot bolting. It has been assumed that for hot bolting, the following circumstances hold:

- Only one bolt will be removed at a time
- The minimum gasket stress will occur in the circumferential midpoint of the gap left by the removed bolt
- The flanges in question conform to ASME B16.5 (Welding Neck Flanges) [*1*]

Therefore, the approach is based on the bolt stress requirement to achieve the appropriate gasket pressure.

***Condition to be satisfied for** "**hot bolting.**"* During operation the residual pressure on the gasket must be "*m*" times greater than the internal pressure in order to avoid the loss of contact between gasket and seats.

Gasket pressure criterion. The required gasket pressure should be taken from ASME BPVC Section VIII - Division 1 [*2*] , where the bolt force to maintain gasket load under operating conditions is defined as W_{m1}:

$$W_{m1} = \left(\frac{\pi}{4} \cdot G^2 \cdot P\right) + (2b \cdot \pi \cdot G \cdot m \cdot P) \tag{1}$$

Where:
P = Internal pressure, MPa
G = Gasket reaction diameter, mm
b = Effective gasket width, mm
m = Gasket factor related to the minimum required load on the gasket for a tight joint, dimensionless

This force, W_{m1}, is composed of the hydrostatic end force due to internal pressure ($\pi G^2 P/4$) and the gasket joint contact load ($2b\pi GmP$).

The term m is a factor specific to the type of gasket used in the joint. The value of $m \times P$ is the stress required in the gasket under operating conditions, and this should be used as the criterion.

In summary, there must be residual pressure on the gasket in order to keep it in contact with the flange surfaces, thus avoiding leakage. The seating force compresses the flanges against the gasket initially, the sealing force is equal to the bolt force. After pressuring the system, the residual pressure on the gasket is equal to the bolt force minus the separation force. The bolt force initially applied to the gasket must compensate for the separation force caused by internal pressure and be sufficient to maintain a residual stress on the gasket, avoiding fluid leakage. From a practical point, in order to maintain the sealing, the residual stress must be a factor m times the fluid pressure.

Flange flexibility

A method for predicting the ratio of gasket stress between bolts is taken from an article by Koves [*3*]. This stress ratio is a function of $\beta \times L$, where L is the distance between bolts and β is defined by the dimensions and material properties of the flange and gasket.

$$\beta = \sqrt[4]{\frac{E_g \cdot b}{2 \cdot t_g \cdot E_f \cdot I_f}} \tag{2}$$

Where:
E_g = Elastic modulus of the gasket, MPa
b = Effective gasket width, mm
t_g = Thickness of gasket, mm
E_f = Elastic modulus of flange, MPa
I_f = Second moment of area of flange, mm^4
$I_f = 0.0874\ (L_c \times g_o^2 \times h_o \times B)/V_c$ (for an integral flange with hub)
L_c = ASME VIII - 1 Code Appendix 2 parameter L , dimensionless
g_o = Small end of hub, mm
h_o = ASME VIII - 1 Code Appendix 2 parameter, mm
B = Flange I.D., mm
V_c = ASME VIII - 1 Code Appendix 2 parameter V, dimensionless
L = Distance between bolts, mm

The Koves article [*3*] gives an equation which relates the ratio of gasket stress between bolts to $\beta \times L$.

This equation is plotted in Figure 2 as a chart of $\beta \times L$ against stress ratio γ, whereas some target values of $\beta \times L$ for specific allowable values of γ are shown in Table 1.

The solution relates the average gasket stress to the stress at the location of the missing bolt using the "Koves" stress ratio. The average gasket stress can be found using the net force over the area of the gasket. Consider the eight bolt flange in Figure 2 with one bolt removed. The average stress in the gasket, σ_{avg}, is a good estimate of the stress at the midpoint between A and B at the middle of the effective gasket width.

$$\sigma_{avg} = \frac{\text{(Total bolt force – Total hydrostatic end force)}}{\text{(Total effective area of the gasket)}}$$

$$\sigma_{avg} = \frac{n_b \cdot F_{bolt} - \frac{\pi}{4} \cdot G^2 \cdot P}{A_{eff}}$$

$$\sigma_{avg} = \frac{F_{bolt} - \frac{\pi \cdot G^2 \cdot P}{4 \cdot n_b}}{A_{eff}} \tag{3}$$

Where:
F_{bolt} = Force from one bolt, N
G = Diameter of location of gasket load = $GO - 2b$, mm
P = Internal pressure, MPa
n_b = Number of bolts, dimensionless
A_{eff} is the area of the gasket compressed by a bolt, which is:
$(1/n_b) \times (\pi/4) \times [GO^2 - G^2]$, mm^2
$A_{total\ gasket} = (\pi/4)[(\text{O.D. gasket})^2 - (\text{I.D. gasket})^2]$
$= (\pi/4)[(\text{O.D. gasket})^2 - (\text{O.D. gasket} - 4b)^2]$
$= (\pi/4)[(\text{O.D. gasket})^2 - (\text{O.D. gasket})^2 - 8b \times \text{O.D. gasket} + 16b^2)]$
$= (\pi/4)(8b \times \text{O.D. gasket} - 8b \times 2b)$
$= \pi \times 2b\ (\text{O.D. gasket} - 2b)$
Since O.D. gasket – $2b$ = G, the total gasket area is $2b\pi G$
The latter is the same as the term in the W_{m1} formula, Equation (1). Therefore,
$A_{eff} = (1/n_b) \times 2b\pi G$
GO = Effective gasket outer diameter, mm; with a maximum of O.D. contact face
$A_{(eff/bolt)}$ compressed by one bolt is: $(1/n_b) \times$ Total effective area of the gasket (A_{eff})

The "Koves" stress ratio, γ, gives the ratio of gasket stresses between B and A of Figure 3, but can also be used to find the stress at B using σ_{avg} if it is assumed that σ_{avg} is the average of the stresses at A and B.

$$\sigma_B = \sigma_A \cdot \gamma \tag{4}$$

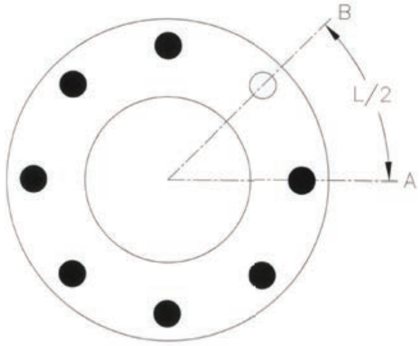

FIGURE 3. This diagram shows a flange face with one bolt missing at B

$$\sigma_{avg} = \frac{\sigma_A + \sigma_B}{2} \quad (5)$$

$$\sigma_B = \frac{2\sigma_{avg}}{\frac{1}{\gamma}+1} \quad (6)$$

The goal is to find the required bolt force so that σ_{avg} is maintained in the gasket. Because a bolt has been removed, F_{bolt} still needs to be corrected as the total bolt force must be supplied by (n_b – 1) bolts. Therefore:

$$F_{bolt} = \frac{\pi \cdot G}{(n_b - 1)} \cdot \left(\frac{G \cdot P}{4} + \sigma_{avg} \cdot 2 \cdot b\right) \quad (7)$$

This criterion gives the required bolt force so that σ_{avg} is maintained in the gasket. If σ_{avg} is set to the gasket pressure criterion F_{bolt} can be related to internal pressure for a specific joint. The properties of the joint being analyzed (materials, dimensions) are contained within the other terms in Equation (7).

For the benefit of the user, a worked example has been added (box) in which the steps to be taken successively lead to a minimum required bolt force that must be present or applied before the bolt to be replaced may be removed.

External flange loads

Special consideration should be given to applications where flanges are subject to significant additional loading. Significant external loading is considered to be a combination of design pressure, external loads and external moments that, when converted to an equivalent pressure, P_{eq} (defined below), are greater than 150% of the flange rated design pressure at design or operating temperature. Where external loading exceeds the 150% value, the

A WORKED EXAMPLE

To help understand the discussion in the main text, a worked example for a welding neck flange (Figure 4) is presented here. The following are the data for the example:

Data

Welding neck flange NPS 12 in. (NB 300) - Class 150 according ASME B16.5 [*1*]
Connecting pipe: O.D. = 323.8 mm; nominal wall thickness: 9.53 mm
Number of bolts: 12; Size of bolts: 7/8 in. UNC - Root area: 270.45 mm^2
Flange material: A105; Bolting material: A193 B7
Gasket: Spiral wound according ASME B16.20; Gasket O.D.: 374.7 mm, Gasket I.D.: 339.9 mm
Bead: 1.5 mm, O.D. effective: 371.4 mm , N = (371.4 – 339.9)/2 = 15.75 mm, b_o = 15.75/2 = 7.875 mm
b = 2.52√7.875 = 7.07, G = 371.4 – 2 (7.07) = 357.26 mm
Design temperature: 300°C ; Rated pressure at 300°C : 10.2 bars = 1.02 MPa
Design pressure: 7 bars = 0.7 MPa
Equivalent pressure converted from imposed external loading: 0.3 MPa
Bolt circle diameter: 431.8 mm , Bolt pitch = 113 mm
E_g = 6895 MPa
t_g = 4.5 mm
E_f = 191000 MPa
I_f = 0.0874 ($L_c \times g_o^2 \times h_o \times B)/V_c$
For an integral flange with hub:
L_c = 0.8633 ; g_o = (0.875 x 9.53) = 8.34 mm; h_o = 53.8948 mm; B = 307.12 mm ; V_c = 0.0533
I_f = 1,629,795.2 mm^4
L = 113 mm

Calculation

The sum of design pressure and equivalent pressure becomes: 1.0 MPa
Required bolt force during operating: Use Equation (1) to find W_{m1}, with P = 1.0 MPa, G = 357.26 mm, b = 7.07 mm and m = 3:

W_{m1} = (π/4)×[(357.26)^2 × 1.0] + (2 ×7.07 × π ×357.26 × 3 ×1.0)

W_{m1} = 147,855 N

Using Equation (2) to determine β:

$$\beta = \sqrt[4]{\frac{E_g \cdot b}{2 \cdot t_g \cdot E_f \cdot I_f}} =$$

$$\sqrt[4]{\frac{6{,}895 \times 7.07}{2 \times 4.5 \times 191{,}000 \times 1{,}629{,}795.2}} = 0.011485$$

When a bolt is removed, the local bolt space becomes twice as large, so for the interval with removed bolt β × L becomes:0.011485[(π × 431.8)/12] × 2 = 2.5966
From Figure 2 it follows that γ = 0.6685
This means that the stress on the gasket at bolt A (of Figure 3) is approximately (0.6685)$^{-1}$ = 1.496 times as great as the stress at bolt B. The least stress on the gasket is at bolt B and it must be so great that there is no leakage. Setting γ = σ_B/σ_A at 0.95, which is desired for leak tightness according Ref. 3, then the mean gasket stress is:

σ_{avg} = (σ_A + σ_B)/2 = (1 + 1/0.95)/2 = 1.0263 × σ_B and σ_A = (0.95)$^{-1}$ × σ_B

The gasket stress in ASME flange calculations is m × P and that is the average gasket stress because, as Koves has shown in Ref. 3), it varies slightly in reality.
So σ_{avg} = m × P = (σ_B+ σ_A)/2 = 1.0263 × σ_B from which it follows that due to "leak tightness," σ_B ≥ 1.0263^{-1} × m × P = 0.975 × m × P. So the minimum gasket stress at the middle of a bolt interval must be at least 0.975 × m × P to avoid leaks. With twice the bolt interval, the gasket stress is:

σ_A = 1.496 × σ_B = 1.496 × 0.975 × m × P = 1.496 × m × P.

And now the minimum required average gasket stress is found:
σ_{avg} = (σ_B + σ_A)/2 = [0.975 × m × P + 1.496 × m × P]/2 = 1.2355 × m × P.

Thus : σ_{avg} = 1.2355 × 3 × 1.0 = 3.7065 MPa
The target bolt force that must be realized before the start of the hot bolting procedure is found using Equation (7):

$$F_{bolt} = \frac{\pi \cdot G}{(n_b - 1)} \cdot \left(\frac{G \cdot P}{4} + \sigma_{avg} \cdot 2 \cdot b\right)$$

$$= \frac{\pi \times 357.26}{(12-1)} \cdot \left(\frac{357.26 \times 1}{4} + 3.7065 \times 2 \times 7.07\right)$$

F_{bolt} = 14,461 N

Note that the recommended (target) torque value for a 7/8 in. UNC stud bolt according to Ref. 4 is 480 Nm and using this will yield a bolt force well in excess of the desired bolt force of 14,461 N.

A bolt torque of 480 Nm achieves a bolt force in the bolt of approximately 108,025 N. If we assume a bolt stress equal to the permissible bolt stress of 172 MPa (according to ASME flange calculation), then the bolt force associated with this stress is 46,612 N. This is a factor 3.2 higher than the minimum required value of 14,461N, which is adequate for avoiding leakage during hot bolting and removal of flange bolts and replacement of them.

The condition associated with the reduction of the effective minimum compressive stress of the gasket between bolts in connection with the removal of bolts is amply satisfied if the stated bolt forces or tightening torque are realized so that sufficient load remains on the gasket to ensure that it maintains a seal. ❒

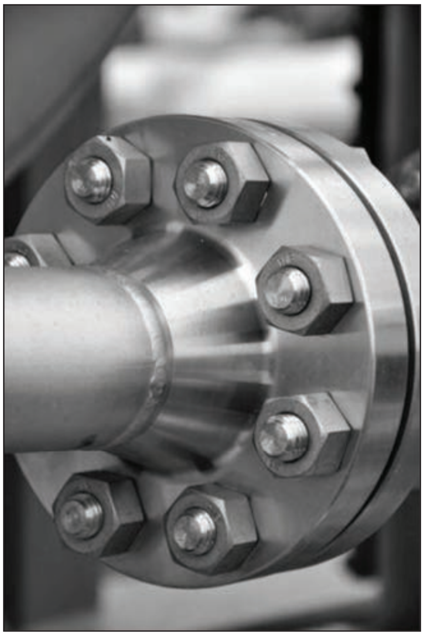

FIGURE 4. A typical welding neck flange is shown in this photo

designer shall consider the need for further evaluation based on known operating experience, consequences of a leak, conservatism of design loading, calculated percentage of flange rated pressure and other relevant influences.

P_{eq} is defined as:

$$P_{eq} = \frac{4}{\pi G^2} \cdot \left(F + \frac{4M}{G}\right)$$

Where
P_{eq} = Equivalent pressure due to external loading, MPa
G = Diameter at location of gasket load, mm
F = External axial tensile load on flange (ignoring compressive loads) for operating condition, N
M = Resultant external moment acting on flange for operating condition, N·mm
The flange design pressure becomes: $P_{eq} + P$.

As an alternative, the following conservative approach may be used. If the magnitude of external loads is not known, this load can be approximated by doubling the internal (design) pressure. The background for this stems from the fact that the ratio between circumferential stress and longitudinal stress in the adjacent connected pipe is a factor of two. This corresponds to a doubling of the force of the adjacent cylindrical part.

Purpose of hot bolting

Hot bolting is the practice of removing and replacing or freeing and re-tightening bolts on live piping and equipment. It is potentially hazardous and the utmost caution needs to be exercised when planning and carrying it out. It is not recommended as best practice although it is widely carried out. However, any potential benefits arising from hot bolting should be carefully weighed against the risks encountered.

Considerations prior to hot bolting

When contemplating hot bolting, a number of factors need to be considered. These include, but are not limited to, the following:

- The operator’s own working procedures and guidelines
- The piping system and the system’s operating pressures and temperatures
- Flange joints considered for hot bolting should have a minimum of eight bolts. The bolt material should have a minimum strength equal to or greater than grades B7/2H
- Prior to the commencement of work, the site supervisor should review the maintenance history of the joint under consideration, and any joints of a similar type which have been hot bolted in the past. Is there any history that should be considered?
- The supervisor should also carry out a visual assessment of the joint. Hot bolting should not be carried out on joints that show significant signs of corrosion or necking, or which have worn or cracked threads on the fasteners
- Hot bolting should only be attempted under operating conditions when the history of the flange assembly is known, that is, records exist for the bolt load
- Hot bolting is not allowed at high temperatures (>300°C)
- The consequences of joint leakage during hot bolting should be considered (for example, toxicity, flammability and temperature of escaping fluids) and all necessary precautions taken. Contingency plans should also be put in place for an escape or emergency, for example, means of communications and provision of standby equipment
- Pipework within the vicinity of the joint to be hot bolted should also be reviewed. Pipe supports for the local section should be checked to ascertain whether they are taking the load on the pipe, along with their overall condition. If the pipework displays any significant signs of vibration around the specific flange, then hot bolting should not be considered as an option ■

Edited by Gerald Ondrey

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For additional articles on bolt loading, see “Standard ASME B16.5 Flanges: Bolt Tightening and Target Loads,” *Chem. Eng.*, December 2019, pp. 38–42; and the online article, “Determination of Nozzle Loads to Facilitate the Initial Pressure Vessel Design,” October 26, 2018, which can be found at www.chemengonline.com.

A System Approach with Flow Analysis

Taking a system approach to find the root cause of a problem can be more beneficial than simply replacing a problematic pump. This article explains why

Ben Keiser
Applied Flow Technology

IN BRIEF

We want the best reliability with anything that we work with. In a plant operation context, how many times do operators find themselves fixing problems and think they are improving reliability by simply buying a "better" pump, valve, process unit and so on? This only treats the symptom and not the root cause and is likely to result in the same problems as before.

There are many opportunities to dramatically improve reliability that are often overlooked. When the plant crew is working tirelessly to maintain day-to-day operation, it is easy to miss critical points that lead to poor system performance, maintenance issues, higher power consumption, downtime, product losses, lower profitability and higher costs. Taking a system approach to reliability improvement has many more benefits than a component approach.

Pump system reliability

If a system approach is so helpful, why might it not be considered? Individual system components are often designed without considering system interactions. Also, the effect of changing system requirements or operation changes may not be fully explored or understood for individual components. Relationships between various system components can be complex and unexpected. Cause and effect may be hard to define, and all parts of the system need to be considered together. More data are often needed for system analysis rather than component analysis.

The U.S. Dept. of Energy with Oak Ridge National Laboratory and Xenergy, Inc. conducted a survey in 1998 in the "U.S. Industrial Motor Systems Opportunities Market Assessment" to determine economically feasible opportunities to improve efficiency and reduce energy costs in industrial systems. The survey found that pump systems account for about 25% of the consumed energy in electric motors. Also, pump systems account for 20–60% of the electrical energy used in various industrial, water, and wastewater treatment facilities [*1*]. As you can see in Figure 1, pump systems have the greatest potential for electrical energy savings.

Pump-system reliability and electrical energy efficiency are closely related to each other. Improvements to pump-system efficiency will have a strong payoff in the electrical energy costs that can be saved. But the dramatic impact on reliability is significant and will be even more appreciated.

According to a Finnish Technical Research Center Report that evaluated close to 1,700 pumps across 20 process plants, the average

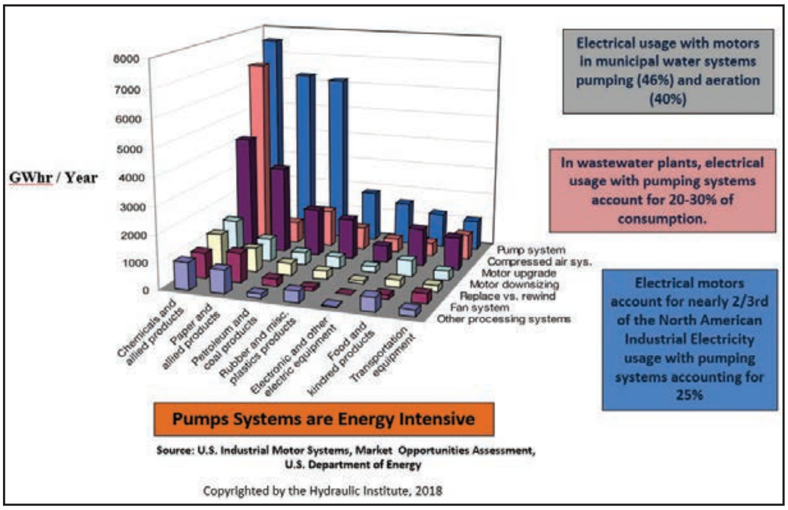

FIGURE 1. Electrical energy consumption of various industrial systems across multiple industries is shown here. Pump systems have greatest potential for electrical energy savings [*1*]

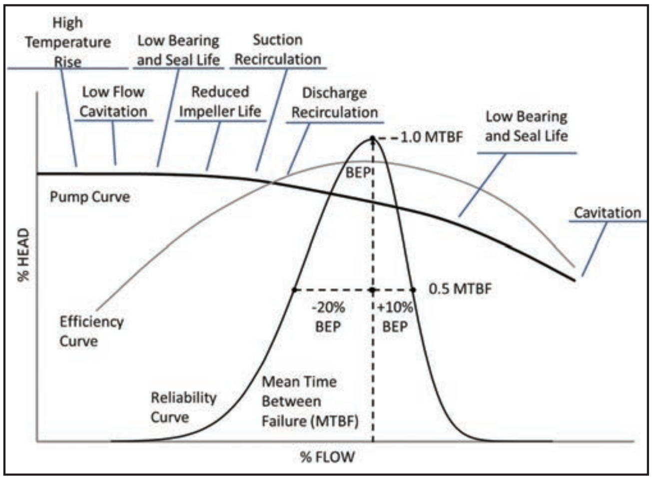

FIGURE 2. The Barringer curve relates pump performance to efficiency and reliability. Pump problems are highlighted in areas when operating outside the preferred operating region (POR) of 80 to 110% of the pump's best efficiency point (BEP)

pumping efficiency was below 40%. In the evaluation, 10% of the pumps operated below 10% efficiency [2]. This is alarming, but probably not surprising. Major contributing factors to minimal efficiency included throttled valves and pump over-sizing. That said, the efficiency value of the pump itself is not the most critical parameter. The best efficiency point (BEP) is of much more importance and is directly related to reliability.

The BEP for a pump is the specific flowrate at which the pump operates where it is most efficient. The primary goal of operation should be to operate as close to this flowrate as possible. When operating at flowrates away from the BEP flowrate, not only will the pump become less efficient, but it will also become less reliable due to various problems that will begin to present themselves.

Figure 2 presents a graph known as the Barringer curve, which relates a pump's efficiency to its reliability. A typical example of a pump curve is plotted with its efficiency curve, which comes directly from the pump manufacturer. The BEP flowrate is identified with a vertical dotted line that crosses the efficiency curve at its maximum value. The reliability curve represents a qualitative measure of a pump's mean time between failure (MTBF). The MTBF is equal to one at the BEP and represents the most amount of time that a pump will be able to operate until a failure of some sort. There are operating envelopes known as the preferred operating region (POR) and the allowable operating region (AOR). The POR is usually dictated by various standards such as ANSI/HI Standard 9.6.3-2017 or ANSI/API 610 11th Edition (2010). The POR brackets the flowrates at which it is desired to operate for as much as possible. Typically, the POR will range from 80% of BEP to 110% of BEP. Note that operating at the boundaries of the POR may reduce the MTBF of the pump by half.

The AOR tends to be a wider envelope where operation is allowed but should be minimized. Typical AOR envelopes might range from 70% of BEP to 120% of BEP.

As you can see on the Barringer curve, significant problems start to occur when operating outside the POR. Issues like higher temperatures, cavitation, recirculation and so on will very quickly take a heavy toll on the pump, seals, bearings and more. Parts start to wear out and repair and maintenance costs become very expensive.

Finding root causes

The problem is that simply replacing these parts or fixing them will only address the symptoms and will never evaluate the root cause that brings these issues about. Why is the pump operating so far away from its BEP? So much is lost when only examining issues on a component-by-component basis. This is where system-level analysis is critical to determining root cause so that these issues can be resolved on a more permanent basis.

How do pumping systems become unreliable and inefficient? Standards for designing pump systems can seem lacking. This tends to cause an over-sizing of pumps, control valves and other pieces of equipment to ensure individual components will work. The engineer adds in a safety factor. Then the reviewer or manager adds on a safety factor, followed by the client, then the pump manufacturer and so on. Now you have an oversized pump with unnecessary safety factors and valves will need to be throttled to meet current demands.

Another cause of a lack of reliability and efficiency is that systems are sometimes designed to meet future requirements, but are operated to meet current market needs. When the pumps are sized for larger flow demands, the operation needs to be modified to meet current demands and this can cause pumps to operate away from their BEP.

System aging and equipment wear also take their toll on reliability and efficiency. Process changes and modifications will have a similar effect that can introduce reliability issues.

Applying a system approach

When applying a system approach of evaluation to pumps and the piping system together, a better understanding is available for complex relationships across all system components. Cause and effect is easier to define. An example would be determining where there are significant pressure drops in the system that affect pump performance. The best part is the ability to consider all parts of the system together to consider all system interactions. This is especially beneficial when evaluating other operating scenarios.

A system approach is greatly streamlined with flow-analysis software. There are many advantages to flow-analysis software to provide better understanding of complex system interactions, including the evaluation of the following:

- Multiple load cases
- Seasonal considerations
- Different operating configurations and requirements
- Waterhammer and cavitation issues
- Choked flow considerations in gas flows

Flow-analysis software also helps with system sizing for pumps, pipes, valves, orifice plates, heat exchangers and so on. Other tasks you can

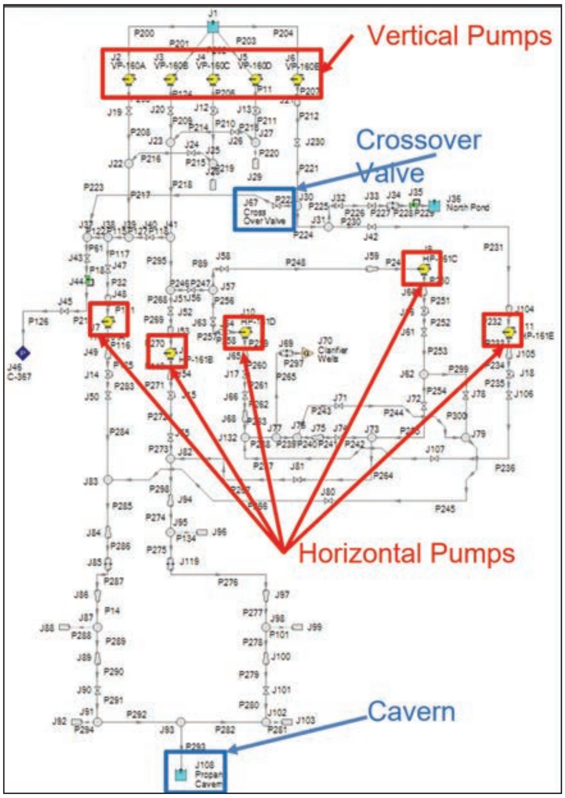

FIGURE 3. Shown here is a piping system flow-analysis model of a raw brine injection system with five vertical pumps in parallel and five horizontal pumps located elsewhere throughout the system

accomplish involve system scale-up evaluation, pressure/flow/temperature distribution, design feasibility analysis, heat transfer, system operation troubleshooting and more. It is also important to quantify pipe system scaling/fouling, pump degradation, code compliance, cost analysis, slurry modeling, pulsation analysis, and more.

What type of information is needed to build a flow analysis model of a pump and piping system? The easy answer is that if it's in the system, include it in the model.

Let's start with the fluid properties. To capture the system hydraulics, the fluid density and viscosity are needed as a minimum. Vapor pressure is important to identify if cavitation is happening anywhere in the system when compared to the static pressure that changes throughout the system. To evaluate heat transfer in the system, thermodynamic properties such as heat capacity, thermal conductivity and enthalpy are needed. If you are modeling compressible-flow situations, other parameters are needed like the universal gas constant, compressibility factor, specific heat ratio, entropy and sonic speed. For a waterhammer simulation, you also need the bulk modulus of elasticity of the fluid, which is an important parameter in the calculation of the wave speed. The wave speed dictates how fast a transient pressure wave in a surge event will propagate through the system. Overall, fluid properties are important, and they need to be accurate.

Information needed to model piping includes the inner diameter, length, frictional information such as roughness, Hazen-Williams factor and elevation changes. This is minimal detail needed for hydraulic calculations. More sophistication can be included where the inner diameter can be determined from a type of material (like steel, HDE, ductile, iron and so on), nominal size, and the schedule or type that is coupled with the wall thickness. This helps match a model to reality a bit more and may be easier than entering an inner diameter directly.

Boundary condition information is required so that the system of fluid dynamic equations can be solved for the piping network. In simplest terms, either a known flow rate boundary OR a known pressure boundary is required. Temperature would be needed for heat transfer calculations. In a flow simulation, it is not possible to specify *both* flow *and* pressure at a boundary, because this would over-constrain the system and the fluid dynamic equations would have nothing to solve for. Therefore, if you specify a pressure boundary, the flowrate from it will be calculated. If you specify a flowrate

boundary, then the pressure at that location will be calculated.

One example of a pressure boundary could be of a large tank. The liquid level and pressure acting on the surface of the liquid is defined, as well as the elevation level of where the pipes are connected. This will allow the pressure to be calculated at the pipe connections, which then gets fed into the system. Doing this can be easier than specifying the pressure directly. Another pressure boundary example would simply be atmospheric pressure, such as if the discharge is flowing into ambient conditions.

Pumps can be modeled in a variety of ways and the data needed depends on the desired information needed. The simplest way is to simulate a pump with a fixed flowrate. The increase in pressure or head that is needed to deliver the specified flow to overcome system resistance and elevation change is calculated. This is very helpful for calculating the operating point needed to size and select a pump. A pump curve provides more information about how the pump will operate. To compare a pump's net positive suction head required (NPSHR) to the net positive suction head available (NPSHA), then the pump's NPSHR as a function of flow is needed from the pump manufacturer. To determine the pump operation proximity to the BEP, or calculate the pump's efficiency, horsepower and so on, an efficiency versus flow, or power versus flow curve is needed from the manufacturer. If a pump is operating with a variable-speed drive (VSD) or variable-frequency drive (VFD), then the speed of the pump can be entered. If a setpoint for flow or discharge pressure applies, then this can be entered as well. Either way, the pump's curve will then be adjusted via the affinity laws.

Large pieces of equipment such as heat exchangers, filters, and others can be modeled in a variety of ways to account for their pressure drop. The most useful is to model a resistance curve where the pressure drop as a function of flow is entered. This will allow the pressure drop across the device to change based upon the flowrate and the behavior often follows a quadratic relationship.

Valves can be modeled in a variety of ways but the input needed often is as simple as a K factor or C_V value. The C_V versus open-percentage data for a valve can also be entered and this provides better understanding of how far open the valves may be. Also, the C_V versus open-percentage data allows one to model the loss across a valve based upon open percentage rather than directly specifying the C_V value.

Minor losses for fittings such as elbows, area changes, orifice plates, and so on, can easily be accounted for with K factors. There are lots of methods available that calculate K factors for these types of fittings and in most flow simulation software tools, these methods are built in. That way K factors can easily be calculated based upon simple input such as upstream and downstream

pipe areas for area change fittings, standard of smooth flanged elbows, long radius elbows and so on.

The more information that is specified, the more accurate the results will be. There are many ways that things can be effectively simplified. However, modeling the system as close to reality as possible is best practice. Even better when test or measured data are available to calibrate a model. A calibrated model that matches data very closely will provide more confidence when it comes to using the model to predict how system changes will impact results and operation.

An example

Figure 3 demonstrates an example of a piping system flow model for a raw brine injection system. There were five vertical pumps in parallel operation and five other horizontal pumps scattered elsewhere throughout the system. The vertical pumps in parallel competed with each other hydraulically and each pump provided significantly different flow than the others. Ideally, the flow distribution should be similar to help all pumps operate close to BEP rather than some pumps operating close to BEP and some operating further away. Within a five-year period, there were a total of 41 repairs, costing near $1.23 million. The MTBF was roughly 15 months.

The consultants on this project were tasked to improve reliability of the system to mitigate the constant repair issues. After the model was built and calibrated, many scenarios were reviewed. The major problem is that the normal operation of the vertical pumps in parallel were operating between 23 and 58% of BEP. Each pump delivered much less flow than its designed capacity. Several scenarios were run that included various system changes such as only operating two of the vertical pumps in parallel instead of three in parallel or more. Other mitigation attempts included closing off a crossover valve as well as increasing the discharge pressure of the cavern.

After all the test scenarios were evaluated, the consultants determined that the combination of only operating two of the vertical pumps in parallel at a time, as well as closing the crossover valve and increasing the cavern pressure, had a dramatic improvement in each pumps' operating proximity to BEP. After these changes, the pumps would then operate at about 75% of their BEP, the flow demands were easily met with only two out of the five vertical pumps and this resolved the many operational problems the facility had.

Final remarks

In conclusion, a system-wide approach for design and analysis of new and existing piping systems can help engineers and owner and operators better understand system interactions and what steps can be made to improve reliability. This is much more useful than a component-by-component approach of constantly repairing parts that wear out or break. Flow-analysis software greatly aids in treating the root cause of the problem rather than the symptom. The flow analysis sheds more light on why pumps, control valves and other pieces of equipment are operating poorly and have problems. The impact of this approach is massive with improved reliability, minimized maintenance and repair costs, downtime, production losses, and increased profits. ■

Edited by Gerald Ondrey

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Field Calibration of DP Flowmeters: Best Practices

Improved understanding of differential pressure (DP) flowmeter operation, along with best calibration practices, reduces maintenance errors

Ned Espy and Roy Tomalino
Beamex

Utilizing an orifice plate installed in a pipe and accurately measuring the differential pressure (DP) to calculate flow is one of most common methods in the chemical process industries (CPI) (Figure 1). DP technology is unique among flow measurement technologies in that the relationship between the flowrate is the square root of the input pressure. This phenomenon presents some challenges to both the vendors that supply DP transmitters and to the technicians that need to calibrate these transmitters.

While new technology available to measure flow can deliver amazing results, and differential pressure flow measurement is widely utilized across many industry sectors, proper use and calibration of these instruments remains important (Figure 2). An improved understanding of the basics of DP flow measurement technology, along with knowledge about the suggested best practices for calibration, will help minimize maintenance mistakes and calibration errors in the field.

Flowmeter requirements

In DP flow measurement, obtaining an accurate result involves more than simply taking the pressure measurement and calculating the output. The accuracy of a DP flow measurement is based on the entire flow-measurement system, including the following: straight runs (upstream and downstream); flow element (orifice plate in good condition); and transmitter (consider "low-flow cut-off" and proper test points).

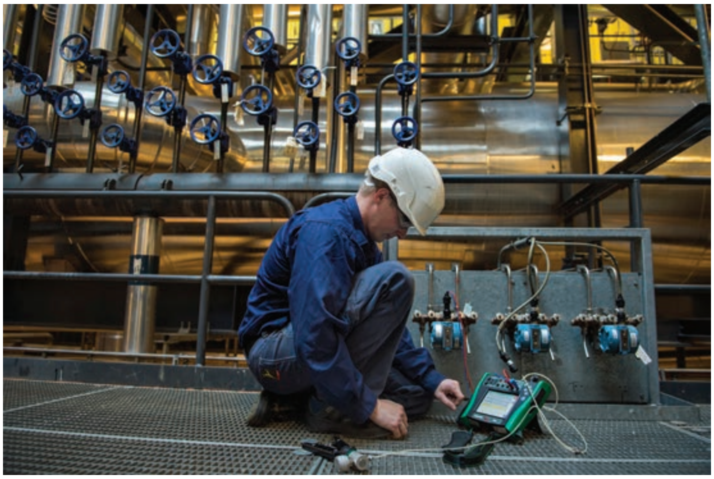


FIGURE 2. Following best practices for calibrating DP flowmeters allows plants to take advantage of the capabilities of new flow-measurement technologies

A "straight run" within the piping upstream of the orifice plate is required for a homogenous and stable flow of fluid through the plate. Likewise, a downstream "straight run" is also required. The orifice plate itself must be clean, with sharp edges and no distortions — inspection of the element should be conducted to verify it is in good condition. The mounting of the plate itself must be carried out with care to ensure a repeatable measurement. Assuming that these physical components are sufficiently addressed, the focus can shift to reviewing the calibration of the DP transmitter to make sure it is accurate.

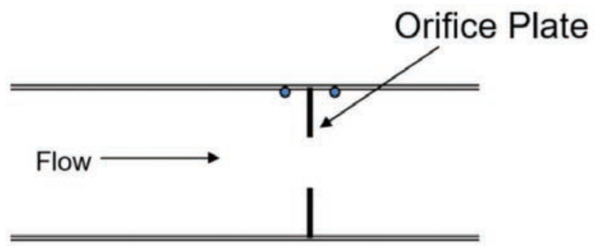


FIGURE 1. Differential pressure (DP) flowmeters measure the velocity of fluids by reading the pressure loss across a pipe constriction, such as an orifice plate like the one shown here

Normally, a pressure transmitter operates in a linear mode from zero to 100% (as an example, at the 50% input pressure level, the output is 50%, or 12 mA).

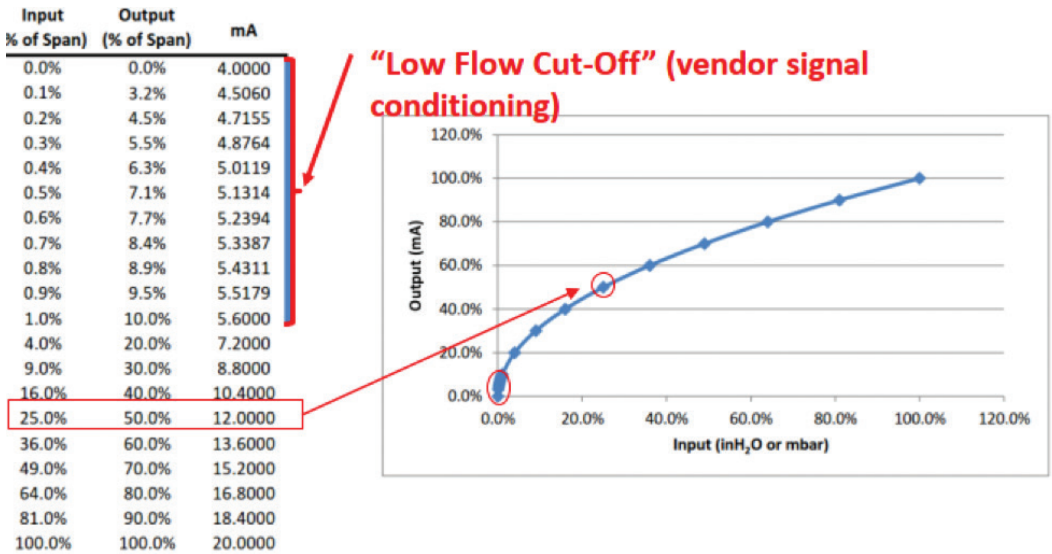
However, a DP transmitter operates in a square-root mode. A common method to verify that a DP transmitter is operating in the square-root mode is to look for a 50% output (12 mA) when the input pressure is 25% of range, using the relationship shown here:

$\sqrt{0.25}$ (input) = 0.50 (output) -or-
0.25 (input) = 0.50^2 (output)

Keep in mind that the square-root calculation is sometimes done in the DCS with the transmitter programmed in a linear mode. So make sure the square root is not being taken twice: once in the transmitter and again in the DCS. Check for that scenario if the numbers are not adding up.

Low-flow conditions

One other issue to consider is when there are low-flow conditions. When the flowrate drops below 10% of the output range of a transmitter (5.6 mA), the input pressure becomes so low (less than 1% of range) that any small change or noise in the pressure input is amplified by a factor of 10 or more. Due to this characteristic, DP flow mea-



Input % of Span)	Output (% of Span)	mA
0.0%	0.0%	4.0000
0.1%	3.2%	4.5060
0.2%	4.5%	4.7155
0.3%	5.5%	4.8764
0.4%	6.3%	5.0119
0.5%	7.1%	5.1314
0.6%	7.7%	5.2394
0.7%	8.4%	5.3387
0.8%	8.9%	5.4311
0.9%	9.5%	5.5179
1.0%	10.0%	5.6000
4.0%	20.0%	7.2000
9.0%	30.0%	8.8000
16.0%	40.0%	10.4000
25.0%	50.0%	12.0000
36.0%	60.0%	13.6000
49.0%	70.0%	15.2000
64.0%	80.0%	16.8000
81.0%	90.0%	18.4000
100.0%	100.0%	20.0000

FIGURE 3. When the flowrate drops below 10% of the output range for a transmitter, as highlighted in the graph, DP flow measurement is no longer accurate

TABLE 1. TEST POINTS FOR CALIBRATION

in. H_2O	mA	
1.450	5.6000	(1.45 in. H_2O is the low-flow cut-off)
36.250	12.0000	
72.500	15.3137	
108.750	17.8564	
145.000	20.0000	

TABLE 2. CALIBRATION TEST POINTS (ALTERNATE METHOD)

in. H_2O	mA	
1.450	5.6000	(1.45 in. H_2O is the low-flow cut-off)
9.063	8.0000	
36.250	12.0000	
81.563	16.0000	
145.000	20.0000	

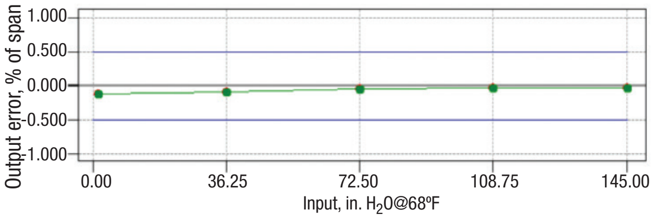
surement is not accurate below this level (Figure 3). Stated another way, the output rises much more rapidly in the initial 0 to 1% of the input, and the signal is very unstable. This situation is the “enemy” of the technician — no quality calibration can be performed in this case.

Another item to note is when using DP flowmeter technology, the normal flowrate is usually much higher than 10%, or there is simply no flow at all (the valve is shut off). DP transmitter manufacturers have had to deal with this low-flow issue and all vendors do some kind of signal conditioning between 4.0 to 5.6 mA. If technicians check with their control engineers, they will likely learn that a “low-flow cut-off” value is programmed into the system. This means that when the transmitter detects somewhere below 10% of the flowrate, the flow is forced to zero.

Based on these facts, when calibrating a DP transmitter, there is no reason to test below 1% of the input range (or 5.6 mA of the output range). In fact, when connected to this type of transmitter, it is very noticeable how the stability “improves” once the pressure is above 1% of the input range.

Calibration test points

Most DP flow applications utilize a low-pressure range input (typically using in. H_2O or mbar as the pressure unit) that is calculated based



Input, in. H_2O @68ºF	Output, mA	Output error, % of span
1.453	5.5814	–0.127
36.252	11.9852	–0.094
72.504	15.3052	–0.055
108.756	17.8503	–0.041
145.023	19.9954	–0.037

FIGURE 4. Calibration data are shown for an example transmitter. with a tolerance of ±0.5% of span

on the size of the orifice plate and the diameter of the pipe. A typical example could have a range of 0 to 145 in. H_2O with a 4–20-mA (square root) output. A normal five-point calibration would have input test points of 0, 25, 50, 75 and 100%. However, dealing with the square-root relationship makes calibration more difficult. The expected output signals would be 4, 12, 15.3, 17.9 and 20 mA. Finally, “low-flow cut-off” should be considered, and the initial test point should be 1% (rather than zero), with an expected output of 5.6 mA. Table 1 shows a summary calibration test point series.

Note that you could also calculate the odd pressure test points that provide an even 25% output step as an alternate method (Table 2; either one is fine).

Figure 4 shows the real calibration data for this example transmitter, with a tolerance that is ±0.5% of span.

This calibration is well within the tolerance (±0.5% of span) with a maximum error of –0.127% of span that occurred at the zero test point. This slight “zero shift” (refer to the graph where the first test point is below the line) only has a 25% significance of the tolerance (0.127% ÷ 0.5%) and no adjustment is recommended. If a lower trim is to be performed, it should be done at the 1% input / 10% output level (not zero).

It is possible that the zero point of the calibration could have been exactly at zero, and the error could have been introduced at one of the middle points of the calibration, or even the span at 100%. The fact that it’s a zero shift is irrelevant to the overall calibration, and it is the overall error allowed for each point that is critical.

When operating the DP flowmeters, the physical components of the system should be checked regularly (orifice plate inspection), and a proper calibration procedure established that addresses the square-root relationship with an initial test point that is slightly above zero to accommodate the “low flow cut-off.” ■

Edited by Scott Jenkins

Acknowledgement

The authors wish to acknowledge David Spitzer, principal at Spitzer and Boyes for contributions to this article. David has more than 40 years of experience in various aspects of instrumentation, and is a leading expert on flow-technology application. For more information about David, visit www.spitzerandboyes.com. To quote David, the problem is, “you cannot put a gallon/minute in your pocket, take to the field and throw it through the flowmeter to check the calibration of the entire flow-measurement system.”

Authors

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Proof-Testing Level-Measurement Devices in Storage-Tank Safety Systems

Storage tanks containing hazardous materials require safety instrumented systems (SIS) to prevent overfills. Digital technology in the latest level-measurement devices used in SIS enables remote proof-testing, which provides significant advantages

AnnCharlott Enberg
Emerson

At industrial facilities with tanks containing hazardous, flammable or explosive materials, the consequences of a safety incident, such as an overfill, can be catastrophic. To minimize risks, storage tanks must have in place robust safety instrumented systems (SIS) that are designed and implemented in compliance with relevant industry standards. Each SIS has one or more safety instrumented functions (SIF), which must be proof-tested periodically. This article discusses proof-testing of safety systems on storage tanks, and the potential advantages available when digital technologies are applied to storage-tank level measurement.

Safety standards

The relevant industry standards for SIS and tank safety are the following:

IEC 61511. The International Electrotechnical Commission's (IEC; Geneva, Switzerland; www.iec.ch) IEC 61511 standard, which outlines best safety practices for implementing a modern SIS within the chemical process industries (CPI). IEC 61511 is an industry-specific adaptation of IEC 61508, which is an industry-independent standard for functional safety.

API 2350. The American Petroleum Institute's (API; Washington, D.C.; www.api.org) API 2350 standard, which provides minimum requirements to comply with modern best practices in the specific application of large, non-pressurized aboveground petroleum storage tanks.

SIS include the level sensors, logic solvers and final control elements, in the form of actuated valve technology, for each of the SIFs — also known as safety loops — that they perform.

Proof-testing

Each SIF within a SIS must be proof-tested regularly. Proof-tests are operational procedures, conducted in accordance with the safety manual of an individual device, whose purpose is to uncover dangerous undetected failures (DUs). These are failures that prevent the device from performing its primary function and remain undetected by the device during normal operation. Proof-testing is a means of verifying that commissioned equipment already in operation will work correctly when there is a safety demand, and that the equipment achieves its required safety integrity level (SIL) for the application. Proof-testing involves testing each of the system's components individually, as well as the complete safety loop. A safety loop's probability of failure on demand (PFD) — that is, the risk of the device failing to perform its intended function — increases over time after commissioning. Performing a proof-test resets the PFD to a lower value and ensures that the safety loop provides the risk reduction it was designed to do (Figure 1).

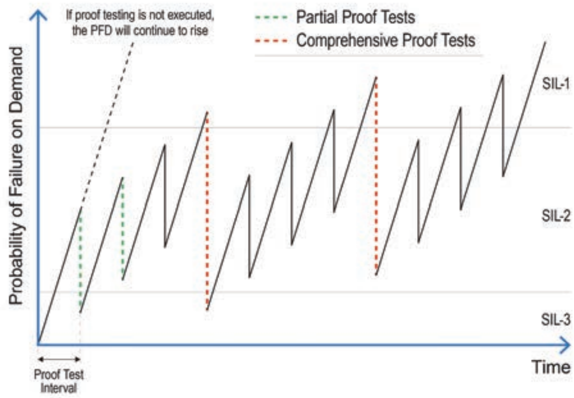

FIGURE 1. A safety loop's probability of failure on demand (PFD) increases over time after commissioning. Performing a proof-test resets the PFD to a lower value and ensures that the safety loop provides the risk reduction it was designed to do

Proof-testing intervals

To create consistency in their approach to safety, many organizations abide by the requirements of both API 2350 and IEC 61511 with regard to proof-testing intervals. IEC 61511 specifies that the entire SIS must be proof-tested periodically, and the frequency of testing is determined by the PFD average of the safety loop. API 2350 states that continuous level sensors should be tested once per year, and point level sensors semi-annually. However, the interval between tests can be extended if there is a technical justification, such as the PFD calculation, to support it. Two types of proof-test — comprehensive and partial — may be performed in compliance with the standards.

Comprehensive proof-testing

Comprehensive proof-tests involve testing the entire safety loop using a single procedure, to ensure all of its parts are functioning correctly. Performing the proof-test will return the PFD of the safety loop back to, or very close to, its original level. Comprehensive proof-testing is carried out manually by multiple technicians in the field, with an-

FIGURE 2. Traditional proof-testing methods on large tanks require operators to enter hazardous locations or work at height to access devices, which poses a potential risk to their safety

other worker stationed in the control room to verify the reaction of the system. There are two different ways in which a comprehensive proof-test can be performed.

In the first method, the level in the tank can be raised to the activation point of the level sensor being tested to provide proof that the instrument is functioning correctly. The danger of this approach is that if the device is a high-level sensor and it fails to activate during the test, this can lead to an overspill that would constitute a safety risk. This method is also time-consuming and can lead to the process being offline for an extended period, with significant cost implications.

The second approach is to remove the instrument from the tank and perform a simulated test in an alternative environment, such as a bucket, for example. A significant disadvantage of this method is that it can involve workers having to climb tanks to access an instrument, thereby putting their safety at risk (Figure 2). Performing proof-tests in this way is also prone to human errors, and can lead to tanks being taken out of service for an extended period, thus affecting profitability. In addition, if the instrument is removed from a tank containing a hazardous or unpleasant product, the test would be performed using water instead. This would fail to prove that the device would work in the specific application.

FIGURE 3. The digital technology available in modern level measurement devices enables operators to perform partial proof-testing remotely from the comfort of the control room

Partial proof-testing

A partial proof-test has reduced diagnostic coverage compared with a comprehensive proof-test because

it is limited to exercising the electronics while the device remains installed. This can verify that there are no faults causing a higher output current than desired, preventing the device driving to low values, or issues preventing the device from driving to higher values. This type of testing may include one or several parts of the safety loop and will bring the PFD of a device back to a percentage of the original level and ensure that it fulfills its specified SIL requirement.

It is important to acknowledge that partial proof-tests complement — but do not replace — comprehensive tests. Because a partial proof-test detects only a percentage of potential failures, a comprehensive proof-test must eventually be carried out after a given time interval to return the instrument to its original PFD. However, performing partial proof-tests can still provide significant benefits for organizations. Partial proof-tests are quicker to complete, require less interference with operations, and crucially, they justify an extension of the time interval required between comprehensive tests, while still remaining within regulatory requirements. This then provides organizations with the freedom to schedule comprehensive tests around planned plant shutdowns, leading to improved plant efficiency.

Proof-test coverage

Smart level measurement devices for overfill prevention applications incorporate diagnostic software that identifies a failure and then takes the device to a safe state. However, some failures are not detected by the diagnostic software — these are the DUs that are revealed during proof-testing. Proof-test coverage is a measure of how many DUs can be detected by the proof-test. Comprehensive tests achieve the highest level of proof-test coverage, as they verify all three functional elements of the device — output circuitry, measurement electronics and sensing element — whereas a partial proof-test verifies one or two of them. However, a combination of partial proof-tests that covers all three functional elements will reach a similar proof-test coverage as a comprehensive test.

Minimizing the DU rate

DUs are measured as failures in time (FITs) and the DU rate is the number of DUs per 10^9 hours. Ideally, the DU rate should be as low as possible, and selecting an instrument that provides a high level of diagnostic coverage will minimize DUs, and therefore make the device less likely to fail in a dangerous way.

Safety lifecycle

IEC 61511 recommends the use of a functional safety lifecycle. This

FIGURE 4. The latest vibrating fork switches can be remotely proof-tested by issuing a HART command. Using this functionality, the proof-test can take less than one minute to complete

involves organizations analyzing hazard levels at their facilities based on risk assessments, selecting reliable level measurement devices for their SIS by considering DU rates,

and checking the ongoing high reliability of devices and safety loops by performing regular proof-tests. Given the importance of DU rates, the reduction of DUs has been a specific aim in the design of the latest level-measurement technology. Advanced diagnostics capability enables the electronic and mechanical health of these devices to be monitored continuously, with the result that the number of DUs is significantly reduced.

Remote proof-testing

Proof-testing has traditionally been conducted on location. However, the digital technology available in modern level-measurement devices enables operators to perform partial proof-testing remotely instead, with the device remaining installed and overfill conditions being simulated to activate the detector and generate an alarm signal (Figure 3). This simulation eliminates the need for fluid to be moved into and out of the tank to perform the test. Simulations avoid the risk of spills, save a significant amount of time and eliminate the need for workers to climb tanks and be exposed to tank contents, thereby increasing worker safety and efficiency. The ability to perform partial proof-testing remotely has become a key selection criterion when implementing level measurement technology as part of a SIS.

Vibrating fork switches. The latest vibrating fork switches for level monitoring can be proof-tested remotely by issuing a HART command (Figure 4). Upon receiving the command, such a device would enter test mode, which cycles the output through wet, dry and fault states, then returns to normal operation. If the proof-test detects an issue, this is reported upon its completion. Using this functionality, the proof-test can take less than one minute to complete, because the instrument remains installed and does not need to be immersed.

FIGURE 5. Powerful and easy-to-use inventory management software enables the latest non-contacting radar level gages to be proof-tested safely and remotely from the control room in under five minutes

Radar devices. Radar is generally the first choice of level measurement technology in a tank gauging system, and the latest non-contacting radar level gages can be proof-tested safely and remotely from the comfort of a control room using powerful and easy-to-use inventory management software. Built-in functionality guides an operator through inputting a straightforward sequence of settings and commands from their interface, enabling a device to be proof-tested in under five minutes (Figure 5). This achieves considerable benefits in terms of reducing risk and errors, saving time, and increasing worker safety and efficiency.

Reference reflectors. Typically, guided-wave radar sensors do not feature overfill simulation technology. However, recognizing the benefits that this feature would provide has led to the introduction of an automated high-level alarm testing function in the latest smart devices. The correct functioning of the high-level alarm can be verified through the use of an adjustable reference reflector fitted to a device's probe at a desired height to generate a unique echo signature. The device constantly tracks the reflector echo to determine if the level is above or below the alarm limit. A "test" function built into the software verifies

that the device has been correctly configured and is correctly tracking the reflector echo. It also confirms that the alarm loop is working, with a high-level alarm being displayed in the control room.

Because this automated testing function does not require the device to be removed from the tank, or the level in the tank to be manually raised, it increases the safety of both the plant and workers. Verification reflector functionality reduces the risk of accidental spills and enables the high-level alarm testing process to be completed more quickly. It also tests the loop from the device to the distributed control system (DCS), as well as the device itself.

Simulated reference reflectors. The high-level alarm can also be verified using a simulated reference reflector, whereby an artificial digital echo is inserted into the radar signal. This artificial digital echo triggers the high-level alarm when detected, thus eliminating the need to have a physical reference reflector. One benefit of this approach is to avoid having a tank obstruction. Performing the test with either a physical or simulated reference reflector as part of a combination of partial proof-tests can achieve a proof-test coverage factor of 73%.

Reporting proof-test results

Both IEC 61511 and API 2350 require organizations to provide written procedures, schedules and documentation of proof-testing. This documentation must include instructions for maintaining safety during the proof-test, as well as actions to be taken upon detection of a fault. Records certifying that tests were completed must be maintained. These should include descriptions of the tests performed, the names of the people that performed them, the dates when they took place, and their results. By providing the reporting functionality to support these requirements, the latest smart level measurement devices and their supporting software ensure compliance with the standards, while simplifying the documentation and auditing process. ■

Edited by Scott Jenkins

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Modernizing the Process Optimization Toolset

Chemical manufacturers are using advanced analytics solutions to transform the way their employees solve data-intensive optimization problems

Allison Buenemann
Seeq Corp.

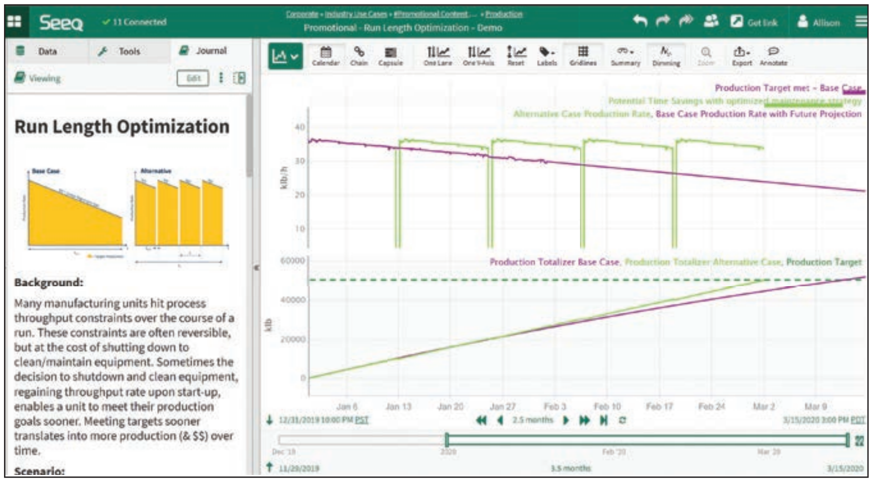

FIGURE 1. These charts depict the optimization problem to be solved (top) and the Seeq Workbench graphical solution to the problem (bottom), respectively

The traditional approach to process-data analysis for optimization has been on-premises process data historian integration with a Microsoft Excel add-in. This methodology requires users to re-query each source system for the event they want to investigate, and to repeat this step over each new time range.

On-premises data sources lack interconnectivity to other data sources, need on-site administration, and require users to be connected to the company network. This rigid architecture means data and analytics have a hard time leaving the literal and metaphorical plant walls, preventing cross-site benchmarking and making a broader organizational analytics strategy infeasible.

However, the past few years have brought tremendous advancements in industry 4.0 technologies, particularly with regard to the democratization of data analytics.

Advanced, cloud-based analytics applications have evoked a paradigm shift in the way engineers think about process optimization and solving other problems involving large amounts of data.

To maintain profitability while addressing environmental and sustainability concerns, the chemical process industries (CPI) must transition its data management and associated analytics capabilities. An early stepping stone in this process is leaning into the cloud as a resource. Embracing the cloud does not mean that a company must migrate all of their existing on-premises data prior to advancing to the next step. They can ease into cloud-based offerings by selecting a cloud-native data-analytics platform that will connect to their data wherever it is currently stored, and where it is going to be stored in the future, as part of their longer-term data strategy. Cloud analytics applications dramatically reduce the time to implement new software solutions and get them into the hands of the end users while improving calculation performance by throttling resources and ultimately reducing information technology (IT) infrastructure and maintenance costs. Cloud-based advanced analytics applications cater to the needs of many user personas with a point-and-click user interface for performing descriptive, diagnostic, predictive, and prescriptive analytics.

The following use cases highlight these evolving methodologies — both for solving difficult problems more efficiently, and for exploring challenges outside the capabilities of legacy analytics tools.

Product run-length optimization

Process effects like fouling or catalyst degradation can cause production rates to become constrained over the course of a product run. These constraints can often be removed by shutting down to perform equipment maintenance, or by performing an online procedure to remove process fouling or plugging. The tradeoffs for performing one of these maintenance procedures can include downtime, rate reductions and quality losses. Evaluating when it makes sense to proactively perform one of these procedures quickly becomes a complex multivariate optimization problem. The goal is to meet production targets in the shortest possible amount of time, which requires additional equipment availability and higher throughput capacity.

Solving this type of advanced optimization problem has historically required expertise in advanced statistical-modeling software and computer programming languages. Drawbacks to these approaches are models are built on static data, are very difficult to deploy and require a long time for retraining with updated process data.

The best deployment option for process modeling is a solution with a live connection to the data source. This is a necessity to ensure that the model can be used in near-realtime applications, with the model continuing to learn and improve based on recent data.

One chemical company was experiencing a degrading production rate over time due to a buildup of polymer skins on the walls of a tubular

reactor. This was restricting flow and increasing the pressure delta, causing it to approach the design limits of upstream equipment.

The company ran at ever-degrading rates until equipment limitations forced them to execute an online procedure that would restore production rates to near the previous maximum, resulting in a few hours of off-specification production. They used Seeq's analytics platform to evaluate this base-case operation against the alternative of proactively performing the defouling procedure to regain throughput capacity.

The advanced analytics application was used to calculate the number of defouling/fouling cycles that would minimize the total production time for a given order quantity. With the optimal number of cycles identified, a predicted degradation rate was calculated and used to build a "golden" profile of the future fouling (running) cycles (Figure 1). As the run progressed, actual production data was compared to the forecast profile to compare performance against the best-case fulfillment date.

Deploying the online model in the advanced analytics application environment allowed it to be used in the early stages of subsequent production campaigns. After observing the fouling rate during the first days of the run, the model was used to identify the optimal number of fouling/defouling cycles, and to calculate a trigger indicating when the online cleaning operation should be performed.

A sold-out production unit implemented this model-based defouling strategy and was able to meet customer orders an average of 11% sooner over the course of the year. In a high-demand market environment, they were able to creep their production capacity, filling the newly tapped reactor availability to grow profit and market share.

Catalyst end-of-run prediction

The fixed bed catalyst in a hydrodesulfurization (HDS) unit degrades over time, impacting product quality. Rate reductions are typically used to hold product quality within limits, but eventually the performance degrades to a point where it is no longer economical to run, at which point the catalyst must be replaced. The replacement typically occurs as part of a coordinated turnaround event, so an accurate prediction of the end-of-life date, well in advance, is required for effective turnaround planning.

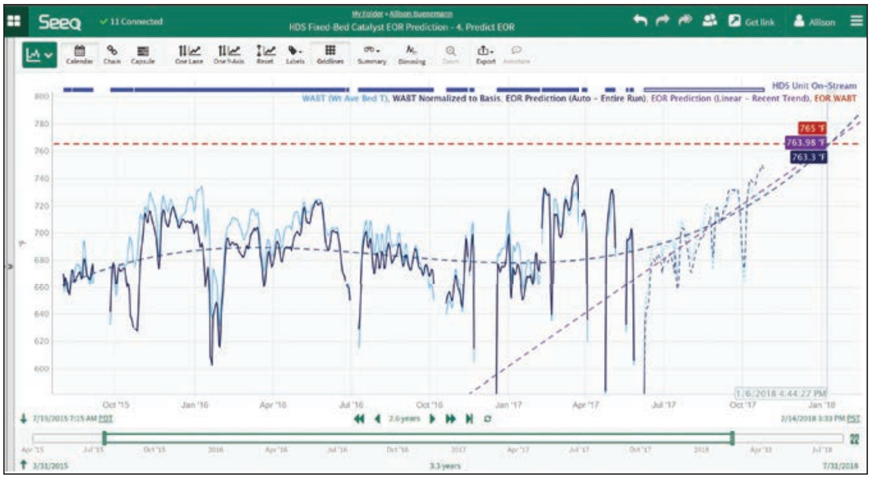

FIGURE 2. Comparison of weighted-average bed temperature (WABT) predictions from the full data set and a recent sample both indicate maintenance requirements in the coming months

The weighted-average bed temperature (WABT) is a key metric often used as a proxy to indicate catalyst bed health. Accurately predicting the WABT for optimized production is challenging as the model must consider expected fluctuations due to adjustments to process variables, such as flowrate and composition. Data cleansing techniques, such as outlier and downtime removal and signal normalization, must be applied to the calculated WABT signal to create a suitable input signal for a regression algorithm.

Process engineers at one large chemical company were investigating whether the degradation rate of their catalyst bed had accelerated in recent months. They used Seeq Formula to create a first-principles model of the WABT, cleansing the signal to only include data when the unit was in operation (Figure 2).

Normalization of the WABT signal was performed using known constants to correct for variability in feed flow and composition. Multiple regression models were developed, and forecasts were extrapolated to predict the required maintenance date. After building these predictive models, it became clear that the degradation rate had become much more aggressive over the last few months, and that their original time-based catalyst changeout would not come soon enough if they continued to operate at current production rates. This analysis justified earlier catalyst change, eliminating months of constrained rate operation and saving over $5 million.

Industry in transition

Chemical companies worldwide must optimize their production processes to increase throughput and flexibility while cutting maintenance costs. Advanced analytics applications are often the best tool to reach these goals, with much less time and effort required from existing staff. These self-service applications empower experts to directly interact with the data sets of interest, providing solutions to many previously intractable problems. ■

Edited by Mary Page Bailey

See the digital version of this article at www.chemengonline.com for additional use cases

Author

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Economic Indicators

2019 — 2020 — 2021

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CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957–59 = 100)	July '21 Prelim.	June '21 Final	July '20 Final
CE Index	720.4	701.4	593.6
Equipment	896.8	868.9	718.8
Heat exchangers & tanks	767.6	745.0	613.0
Process machinery	913.5	876.6	719.8
Pipe, valves & fittings	1,245.0	1195.9	945.8
Process instruments	531.4	521.9	415.9
Pumps & compressors	1,151.5	1125.8	1083.5
Electrical equipment	614.5	609.8	563.1
Structural supports & misc.	974.8	940.0	760.8
Construction labor	344.6	341.9	337.4
Buildings	765.3	763.8	594.2
Engineering & supervision	311.1	310.6	312.2

Annual Index:

2013 = 567.3

2014 = 576.1

2015 = 556.8

2016 = 541.7

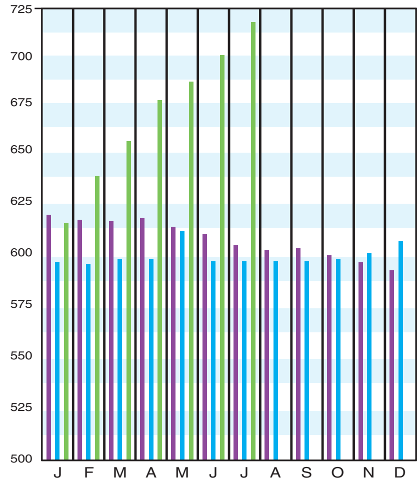
2017 = 567.5

2018 = 603.1

2019 = 607.5

2020 = 596.2

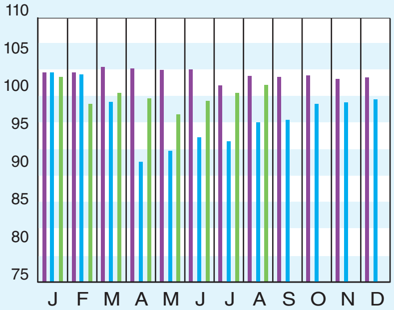
Starting in April 2007, several data series for labor and compressors were converted to accommodate series IDs discontinued by the U.S. Bureau of Labor Statistics (BLS). Starting in March 2018, the data series for chemical industry special machinery was replaced because the series was discontinued by BLS (see *Chem. Eng.*, April 2018, p. 76–77.)



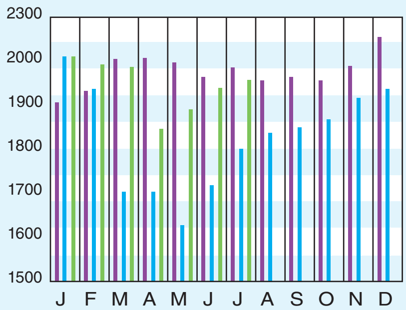
CURRENT BUSINESS INDICATORS

	LATEST	PREVIOUS		YEAR AGO
CPI output index (2017 = 100)	Aug. '21 = 98.3	Jul. '21 = 95.0	Jun. '21 = 95.0	Aug. '20 = 91.6
CPI value of output, $ billions	Jul. '21 = 1,965.7	Jun. '21 = 1,761.8	May '21 = 1,761.8	Jul. '20 = 1,638.6
CPI operating rate, %	Aug. '21 = 78.4	Jul. '21 = 75.6	Jun. '21 = 75.6	Aug. '20 = 72.6
Producer prices, industrial chemicals (1982 = 100)	Aug. '21 = 331.0	Jul. '21 = 240.0	Jun. '21 = 240.0	Aug. '20 = 224.3
Industrial Production in Manufacturing (2017 =100)*	Aug. '21 = 99.7	Jul. '21 = 96.8	Jun. '21 = 96.8	Aug. '20 = 94.1
Hourly earnings index, chemical & allied products (1992 = 100)	Aug. '21 = 195.4	Jul. '21 = 194.3	Jun. '21 = 194.3	Aug. '20 = 188.8
Productivity index, chemicals & allied products (1992 = 100)	Aug. '21 = 94.5	Jul. '21 = 92.1	Jun. '21 = 92.1	Aug. '20 = 89.0

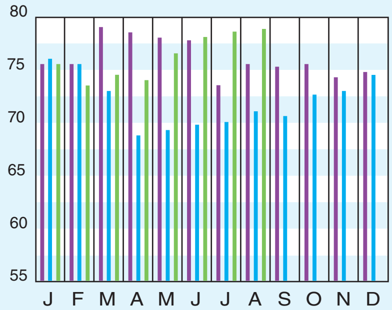
CPI OUTPUT INDEX (2017 = 100)†



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.
†For the current month's CPI output index values, the base year was changed from 2012 to 2017
Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The preliminary value for the *CE* Plant Cost Index (CEPCI; top) for July 2021 (most recent available) continued the string of sizable monthly increases from the beginning of the year. In July, all four of the major subindices (Equipment, Buildings, Construction Labor and Engineering & Supervision) saw increases, with the largest uptick observed in the Equipment subindex. The current CEPCI value represents a 21.4% change over a year ago at the same time. Meanwhile, the Current Business Indicators (middle) show an increase in the CPI Output Index for August, as well as an increase in the CPI Value of Output for July. In addition, the CPI Operating Rate and Productivity Index rose in August.